Flawed Technology of Subtitle D Landfilling of Municipal Solid Waste

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Abstract

This report presents a review of the information available pertinent to public health and environmental quality protection issues for proposed Subtitle D landfills. Based on this review it is concluded that this type of landfill will at most locations cause groundwater pollution by landfill leachate and be adverse to the health, welfare and interests of nearby residents and property owners/users. As discussed, there is normally significant justification for those near a proposed Subtitle D landfill to oppose the development of the landfill.

Typically landfilling regulations require that,

> *(a) the solid waste facility shall not pose a substantial endangerment to public health or safety or the environment;*
> *(b) the solid waste facility shall not cause an environmental nuisance.*

Frequently in review of a proposed landfill, the regulatory agency staff do not adequately or reliably evaluate the potential for a proposed landfill to endanger public health, safety and the environment, and cause nuisance on adjacent properties.

Subtitle D landfills have the potential to generate leachate (garbage juice) that will pollute groundwater with hazardous and deleterious chemicals that are a threat to human health and the environment for thousands of years. These landfills have the potential to generate landfill gas that will contain hazardous and obnoxious chemicals for a long period of time well beyond the current 30-year funded postclosure period. Specific deficiencies in the siting, design, operation, closure and postclosure care provisions for Subtitle D landfills include:

- a single composite landfill liner that will eventually fail to prevent leachate pollution of groundwater,
- a landfill cover that will eventually allow rainfall to enter the landfilled wastes which will generate leachate that will pollute groundwater,
- a grossly inadequate groundwater monitoring system that has a low probability of detecting leachate-polluted groundwater before it leaves the landfill owner's property,
- inadequate postclosure funding for landfill monitoring, maintenance and remediation of polluted groundwater for as long as the wastes in the landfill will be a threat,
- inadequate buffer lands between where wastes will be deposited and adjacent properties, which will result in adverse impacts on nearby property owners/users from landfill releases, including odors, dust, vermin, and noise and lights from landfill activities,
- decreased property values for owners of nearby properties.

In addition, at some locations there is an environmental justice issue associated with the development of a landfill that will be adverse to minority communities.

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Acronyms and Definitions

C&D	construction and demolition
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CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CIWMB	California Integrated Waste Management Board
CWA	Clean Water Act
FML	flexible membrane liner
GAO	General Accounting (Accountability) Office (federal)
GCL	geosynthetic clay liner
HDPE	high-density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance (model)
LDEQ	Louisiana Department of Environmental Quality
LEL	lower explosive limit
MCLs	maximum contaminant levels
Mil	thousands of an inch
MSW	municipal solid waste
NIMBY	"not in my back yard"
OEHHA	Office of Environmental Health Hazard Assessment (California)
PBDEs	polybrominated diphenyl ethers
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
POTWs	publicly owned treatment works (domestic wastewater treatment plants)
PPCPs	pharmaceuticals and personal care products
RCRA	Resource Conservation Recovery Act
SWANA	Solid Waste Association of North America
SWAT	Solid Waste Assessment Test
SWRCB	State Water Resources Control Board (California)
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
US EPA	US Environmental Protection Agency
VOCs	volatile organic solvents

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Overview of Landfilling Regulations

In 1991 the US EPA (1991) promulgated regulations for landfilling of municipal solid wastes (MSW). These regulations cover Resource Conservation Recovery Act (RCRA) Subtitle D requirements mandated by the US Congress. These regulations establish the "dry tomb" landfilling approach, where the MSW to be landfilled is entombed in a plastic sheeting and compacted soil/clay liner and cover. The Subtitle D regulations established a national minimum design standard requiring a single composite (plastic sheeting and compacted clay) bottom liner and a landfill cover that is no more permeable than the bottom liner. A groundwater monitoring program is to be established that in principle can detect landfill-leachate-polluted groundwater when it first reaches the point of compliance for groundwater monitoring. The groundwater monitoring program includes monitoring to define the extent of groundwater pollution when it is detected at the point of compliance. Further, the polluted groundwater is to be remediated (cleaned up). This approach has the purpose of preventing offsite (adjacent property) groundwater pollution by landfill leachate. Landfill gas is to be collected/managed to prevent offsite explosive hazards. These regulations also establish a minimum 30-year postclosure landfill monitoring and maintenance period that may be extended at the discretion of the US EPA Regional Administrator. There are also some restrictions on the siting of landfills with regard to flood plains, near airports, and near earthquake faults.

In the mid- to late 1980s, considerable research was undertaken on the properties of plastic sheeting liners. It was well established that the plastic sheeting flexible membrane liner (FML) and compacted clay had significant problems in preventing moisture from entering the landfill through the cover and in collecting the leachate (garbage juice) that is generated in the landfill when water enters the wastes. In 1998 the US EPA draft Subtitle D regulations included statements (see below) that it was understood that a single composite liner would eventually deteriorate and fail to prevent groundwater pollution.

One of the major driving forces for **not** developing landfills that would be protective of public health and the environment for as long as the wastes in a MSW landfill would be a threat was the concern that developing this type of landfill would significantly increase the cost of municipal solid waste management. The national administration, through several administrations, did not want to have to face the public opposition associated with increasing the cost of household and industrial solid waste disposal.

In the early 1990s there was growing concern that the entombment of MSW in plastic sheeting and compacted clay would not be effective in preventing leachate pollution of offsite groundwaters for as long as the wastes in the dry tomb landfill would be a threat. Based on an understanding of the processes that take place in a MSW landfill, it is obvious that keeping the wastes dry would lead to a situation where no waste decomposition would occur, and therefore the wastes would be a threat to generate leachate, effectively forever – well beyond the 30-year postclosure period of required funding. There was growing recognition that the dry tomb landfilling approach with compacted soil and plastic sheeting liner and cover was not a reliable approach for preventing groundwater pollution for as long as the wastes in a minimum Subtitle D landfill would be a threat. This led to the US EPA's delaying the promulgation of the Subtitle D regulations beyond the due date that Congress had established. An environmental group filed suit against the US EPA to force the Agency to promulgate the Subtitle D regulations, with the result that the current Subtitle D regulations were adopted in 1991, even though it was well understood that landfills that conformed to these regulations would not be protective of public health and the environment for as long as the wastes in the landfill would be a threat.

Typically when private companies and/or public agencies propose to construct a municipal solid waste (MSW) landfill in an area, the residents/property owners of the area oppose the development of the landfill. This report presents a review of the information available pertinent to this issue and concludes that typically proposed Subtitle D landfills will cause groundwater pollution by landfill leachate and be adverse to the health, welfare and interests of the residents and property owners in the area of the landfill. As discussed herein, normally there is significant justification for opposition to the development of Subtitle D landfills by those within the sphere of influence of the landfill.

Qualifications to Provide Comments

Information on Drs. G. F. Lee and Anne Jones-Lee's qualifications to provide these comments is summarized below. G. F. Lee earned a bachelor's degree in environmental health sciences from San Jose State College in San Jose, California, in 1955. His undergraduate education included work on public health aspects of landfilling of municipal solid wastes. He obtained a Master of Science in Public Health degree from the University of North Carolina, Chapel Hill, in 1957, and a PhD degree in Environmental Engineering from Harvard University in 1960. Both his masters and PhD degree work included studies on water quality, public health, and waste management.

For 30 years he held teaching and research positions in graduate-level environmental engineering/environmental science programs at several major US universities. During that time he conducted more than $5 million in research and published more than 500 papers and reports on various aspects of water quality and the impact of chemical contaminants on public health and environmental quality. His work included investigating numerous municipal solid waste landfills and conducting research for the US EPA and others on landfill liner properties. In 1989 he retired from university teaching and research and expanded his part-time, private consulting activities into a full-time business. He was joined in that work by his wife, Dr. Anne Jones-Lee, who at that time held a professorship in environmental engineering/science. Since that time they have been active in investigating more than 80 municipal solid waste landfills located in various parts of the US and other countries. They have published more than 650 additional papers and reports, approximately 120 of which are devoted to landfill pollution issues.

In 1992 Drs. Lee and Jones-Lee developed a "flawed technology" review (Lee and Jones, 1992), in which they summarized the significant potential problems with Subtitle D landfilling with respect to protecting public health and the environment for as long as the wastes in the landfill will be a threat. Throughout the 1990s Drs. Lee and Jones-Lee developed several papers and reports that provided further information on the potential problems with Subtitle D landfilling. A comprehensive review of these issues was published by Lee and Jones (1991). The discussion presented herein represents an integration of the current understanding of the problems with Subtitle D landfilling of municipal solid waste. Additional information on Drs. G. F. Lee and

Anne Jones-Lee's experience and expertise in evaluating landfills' public health and environmental impacts is available from www.gfredlee.com, at http://www.gfredlee.com/landfill.htm.

In the discussion presented herein, statements/approaches that are advocated by landfill proponents are presented. These statements are typical of the types of statements that are made by landfill developers and regulatory agency staff that support the development of a minimum Subtitle D landfill.

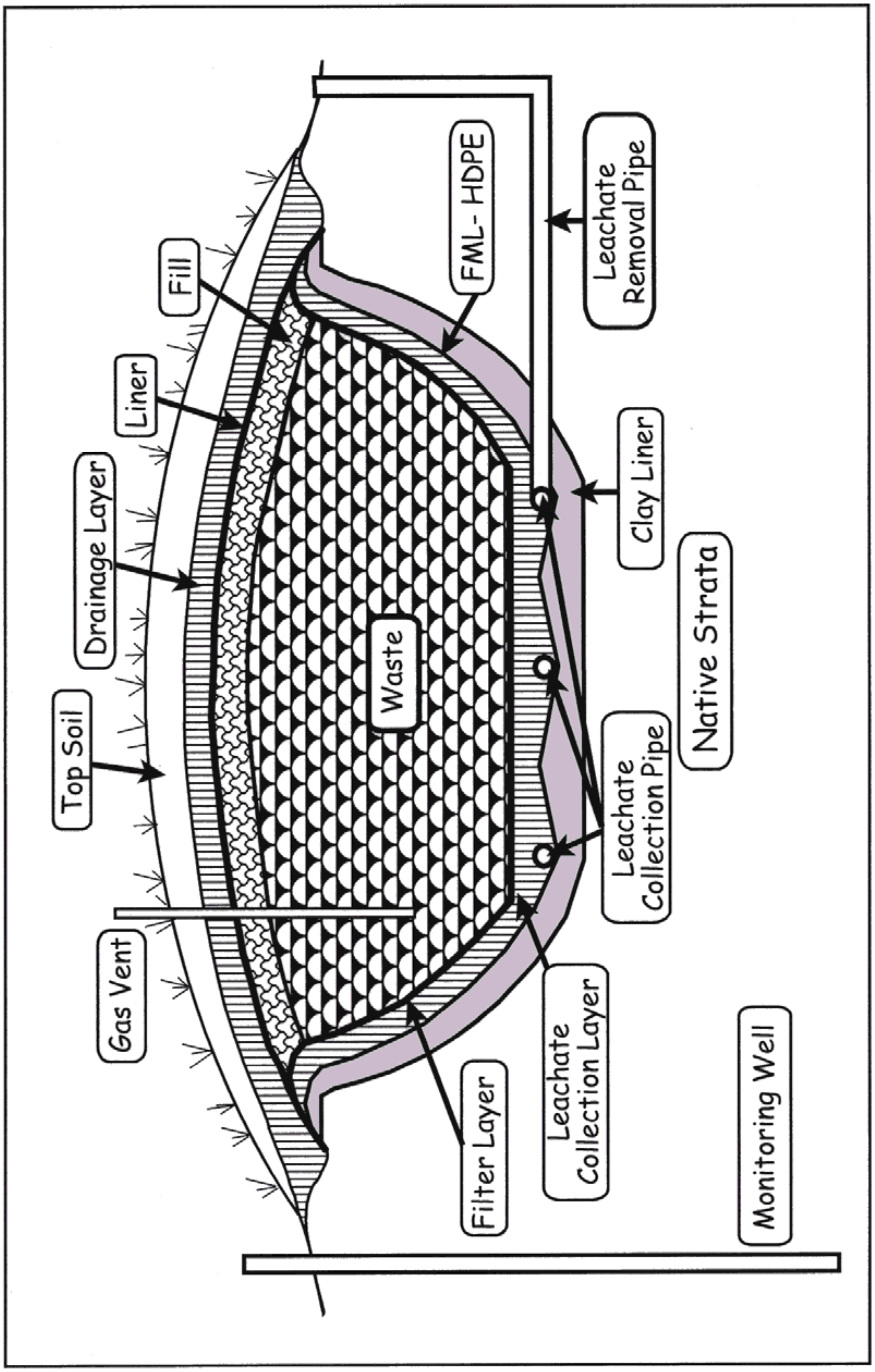
Evolution of Subtitle D Landfills

Traditionally, the landfilling of solid wastes has been accomplished at the least possible cost. Initially, urban areas deposited their solid wastes on nearby low-value lands, frequently wetlands, creating a waste dump. This approach was followed by excavation of an area and depositing the wastes in the excavated area. Often the wastes in the dump were burned to reduce volume and some other adverse impacts. Eventually, beginning in some areas in the 1950s, it was determined that there was need to cover the daily deposited wastes with a layer of soil to reduce odors and access to wastes by vermin, rodents, flies, birds, etc. This approach led to the development of the "sanitary" landfill. Basically, the sanitary landfill was an excavated area in which the wastes were supposed to be covered each day by a layer of soil. No regard was given to the potential for the wastes in a sanitary landfill to cause groundwater pollution or for the gas generated in the landfill to be a threat to cause explosions and to cause public health and environmental problems. While landfilling in the conventional sanitary landfill was recognized in the 1950s as leading to the pollution of groundwater by landfill leachate (ASCE, 1959), it was not until the 1980s/1990s that there were national regulations that were designed to control groundwater pollution by landfills. In the 1980s the US EPA and state regulatory agencies adopted the "dry tomb" landfilling approach.

In accordance with current US EPA regulations, solid waste landfills today are of a "dry tomb" design and, in principle, operation. Environmental groups in the early 1980s convinced the US Congress and the US EPA that landfilling should be based on the concept of isolating the waste from water that can generate leachate (garbage juice) that can in turn lead to groundwater pollution by constituents leached from the solid waste. In theory, since one of the primary problems of solid waste landfills that are used to manage municipal or industrial solid waste is the pollution of groundwater by leachate, if the waste could be isolated from water that leads to the formation of leachate, then groundwater pollution by landfills could be prevented. The dry tomb landfilling approach, however, leads to a situation where the wastes that are isolated from the environment in a compacted soil and plastic sheeting "tomb" will remain a threat to cause groundwater pollution and to generate landfill gas.

The dry tomb landfilling approach (see Figure 1), as implemented by the US EPA, is based on the use of a relatively thin plastic sheeting (high-density polyethylene – HDPE) layer and a compacted soil/clay layer to form what is called a "composite" liner. The evolution of this approach began in the 1970s, when compacted soil/clay liners were proposed for landfills.

Figure 1
Single Composite Liner Landfill Containment System



However, this did not prevent the wastes in the landfill from causing groundwater pollution. Further, the clay liners were found to be subject to a number of problems that led to their failure to prevent leachate from passing through them at the design characteristics.

The fact that compacted soil layers cannot prevent groundwater pollution by landfill leachate led the US EPA in the early 1980s to adopt the use of a plastic sheeting layer as a liner. However, that approach was soon found to be unreliable, since relatively small holes in the plastic sheeting could lead to high leakage rates through it. The next approach adopted was that of a composite liner, in which the high-density polyethylene plastic sheeting is laid immediately adjacent to the compacted soil/clay layer. This approach can greatly decrease the rate of leakage through the plastic sheeting liner, where there are only a few holes in the plastic sheeting, if the clay and the plastic sheeting layers are in intimate contact.

The evolution of liner and cover systems for landfills – from no liner, to a clay/soil liner, to a plastic sheeting liner, to the current composite liner – was not based on a finding that any of these liners could potentially prevent groundwater pollution by wastes for as long as the wastes in the containment system were a threat. The clay/soil liner was based on using the next least expensive material to no liner. When it was realized that clay/soil liners had significant problems, plastic sheeting was the next least expensive to clay/soil. There was never an evaluation that showed that clay/soil or plastic sheeting would be expected to prevent groundwater pollution for as long as the wastes were in the landfill. The same situation applies to the composite liner system that is used today. It is only a matter of time until that liner system fails to prevent leachate from passing through it which can pollute groundwaters, rendering them unusable for domestic and many other purposes.

The US EPA, as part of adopting the RCRA Subtitle D regulations, stated in the draft regulations (US EPA, 1988a),

> *"First, even the best liner and leachate collection system will ultimately fail due to natural deterioration, and recent improvements in MSWLF (municipal solid waste landfill) containment technologies suggest that releases may be delayed by many decades at some landfills."*

The US EPA (1988b) Criteria for Municipal Solid Waste Landfills stated,

> *"Once the unit is closed, the bottom layer of the landfill will deteriorate over time and, consequently, will not prevent leachate transport out of the unit."*

With this background of the ultimate long-term failure of the landfill containment system, it is appropriate to inquire as to why the US EPA adopted a fundamentally flawed approach for landfilling of wastes. This situation arose out of the fact that environmental groups had filed suit against the US EPA for failure to develop municipal and industrial "nonhazardous" solid waste landfilling regulations. This led the Agency to promulgate the Subtitle D regulations (US EPA, 1991), based on a single composite liner and equivalent landfill cover, even though it was understood in the early 1990s that at best this approach could only postpone when groundwater pollution occurs by landfill leachate.

For a number of years following the adoption of the Subtitle D regulations, US EPA management indicated that the problems with Subtitle D landfills discussed in the draft regulations still existed, and acknowledged that ultimately the liner system will fail to prevent groundwater pollution. Lee and Jones-Lee (1998a), as part of preparing an updated review of their 1992 “flawed technology” report, contacted the US EPA administration to ascertain if this administration had changed the conclusion reached by the US EPA 1988 administration that a single composite liner would, at best, only delay when groundwater pollution occurs by landfill leachate (Clay, 1991). Dellinger (1998), head of the Office of Solid Waste and Emergency Response for the US EPA, indicated that the Agency still concluded that a single composite liner will ultimately fail to prevent leachate transport through it.

Recently, under the current administration, the US EPA has been espousing on its website a different position, intimating that minimum Subtitle D landfill liner systems – which have not changed – now will be protective. Lee (2003a) discussed the unreliable information that is now being provided by the US EPA on the ability of a minimum Subtitle D landfill’s design, closure and postclosure care to protect public health and the environment for as long as the wastes in a dry tomb type landfill will be a threat. As discussed below, the US EPA’s revised position is not based on a technically valid assessment of the length of time that the waste in a municipal solid waste dry tomb landfill will be a threat to generate leachate and the duration that a minimum Subtitle D single composite liner can be expected to collect all leachate generated in the landfill and thereby prevent groundwater pollution by it.

The 30-year funding period for postclosure monitoring and maintenance of Resource Conservation and Recovery Act Subtitle C and D landfills that was specified by Congress was one of the most significant errors made in developing RCRA Subtitle C (hazardous waste) and D (municipal solid waste) landfilling regulations. In establishing the original RCRA landfilling regulations, the environmental groups and Congress, apparently with US EPA approval, had no understanding of the length of time that municipal or industrial waste in a dry tomb landfill would be a threat to cause groundwater pollution when moisture (water) infiltrates into the landfill. There was the mistaken idea that 30 years after closure of a dry tomb landfill, the waste in the landfill would no longer be a threat. Those who understand the characteristics of wastes and their ability to form leachate, as well as the processes than can occur in a landfill, realize that 30 years is an infinitesimally small part of the time that waste components in a landfill, especially a dry tomb landfill, would be a threat to cause groundwater pollution through leachate formation. While Congress required that the regulations include provisions to potentially require additional funding at the expiration of the 30-year postclosure care period, the likelihood of obtaining this funding from private landfill companies, even if they still exist 30 years after a landfill has been closed, or from a public agency that develops or owns a landfill, is remote.

A review of the properties of municipal solid wastes and how they degrade/decompose in a landfill shows that the rate of decomposition is dependent on the amount of moisture that enters the landfill. Water is needed by bacteria that are present in the landfilled wastes in order to decompose those parts of the waste that are subject to bacterial decomposition. These issues have been discussed by Christensen and Kjeldsen (1989). This decomposition leads to landfill gas production. Another mechanism for decomposition of municipal solid waste components is the leaching (dissolving) of waste components to produce leachate. In a true dry tomb landfill, the wastes are kept dry and, therefore, do not decompose or leach. Under this condition, the wastes will forever be a threat to generate landfill gas and leachate. This situation necessitates that the landfill bottom liner collect all leachate that is generated for as long as the wastes are a threat (forever). Further, the landfill cover must be designed, operated and maintained to greatly restrict the amount of moisture that enters the landfilled wastes through the cover, forever.

As noted by John Skinner, Executive Director of the Solid Waste Association of North America (SWANA) and former US EPA official in the Office of Solid Waste and Emergency Response, on pg.16 of the July/August 2001 *MSW Management* Journal,

> *"The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and someone needs to be responsible for stepping in and taking corrective action when a problem is detected."*

Leachate Generation Potential Will Continue for Thousands of Years. The municipal solid wastes (MSW) in a classical sanitary landfill where there is no attempt to prevent moisture from entering the wastes have been found to generate leachate for thousands of years. Freeze and Cherry (1979) of the University of British Columbia and the University of Waterloo, Ontario, Canada, in their book, Groundwater, discuss that landfills developed in the Roman Empire about 2,000 years ago are still producing leachate. Belevi and Baccini (1989), two Swiss scientists who have examined the expected contaminating lifespan of Swiss MSW landfills, have estimated that Swiss landfills will leach lead from the waste at concentrations above drinking water standards for over 2,000 years. Based on the information in these references, a proposed Subtitle D dry tomb landfill will be a threat to groundwater resources for long periods of time, effectively forever. These issues are discussed further in the papers, "Landfilling of Solid & Hazardous Waste: Facing Long-Term Liability" (Lee and Jones-Lee, 1994a), "Landfill Leachate Management," (Lee and Jones-Lee, 1996) and "Groundwater Pollution by Municipal Landfills: Leachate Composition, Detection and Water Quality Significance" (Jones-Lee and Lee, 1993).

Another significant error that was made in developing the dry tomb landfilling approach was that it was assumed that it would be possible to design, construct and operate the landfill containment system so that little or no moisture could enter the landfill once the landfill was closed – i.e., no longer accepting waste – and a landfill cover had been placed on the waste. Further, it was assumed that, even if moisture did get through the low-permeability cover of the landfill, the leachate generated would be collected in a leachate collection system which overlies the single composite liner. Further, the US EPA assumed then (and, unfortunately, still assumes today) that, when a dry tomb landfill generates leachate that passes through the liner into the underlying geological strata and groundwater system, the groundwater monitoring system used would detect this leachate-polluted groundwater while the leachate-polluted groundwater was still on the landfill owner's property. Unfortunately, these assumptions were based on inappropriate analysis, and it is now clear that the dry tomb landfill is a **fundamentally flawed technological approach** for managing solid waste.

Effect of Climate on Leachate Generation. During the active life of the landfill (while wastes are being accepted), landfills located in wet climates such as the Northwest, Midwest, South and East generate leachate proportional to the precipitation. Once the landfill cover is placed over the wastes, leachate generation is dependent on the ability of the cover to prevent infiltration of moisture into the wastes through the cover. Landfills located in the arid west produce less leachate than landfills located in wetter climates; however, the leachate produced by such landfills still poses a significant threat to cause groundwater pollution.

In 1984 the California legislature passed a law requiring the testing of water and air at all solid waste disposal sites. This program became known as the Solid Waste Assessment Test (SWAT) program. In 1995 Mulder and Haven (1995) presented a report of the results of the testing that had been done at 544 landfill sites in California. They reported that 72 percent of the sites tested had been found to have leaked waste constituents from the waste management unit. Only 14 percent were found to be not leaking, a finding that may reflect more the adequacy of the SWAT investigation than the lack of leakage. Another 14 percent was "undetermined" with respect to leaking leachate. Mulder and Haven (1995) concluded,

> *"Available data indicate no apparent correlation between the percentage of landfills which leaked and any of the different site-specific factors checked, including depth to ground water, average annual precipitation, waste acceptance rate, and rock type."*

The California SWAT results have pertinence to the potential for landfills located in arid areas to pollute groundwaters, since some of the California landfills that have been found to be leaking leachate are located in an arid climate. The results of the SWAT investigations were for unlined landfills or landfills that had been constructed since 1984, which was the date that California landfilling regulations (Chapter 15) required that all new landfills or landfill expansions contain a clay liner. Mulder and Haven reported that there was no difference between the leakage of clay-lined landfills versus unlined landfills – i.e., the lining of a landfill with a clay liner did not prevent groundwater pollution.

Recently, Lee and Jones-Lee (2006a) have discussed groundwater quality protection issues, focusing on land surface activities, including landfills, that can lead to groundwater pollution. They have provided a chronology of the landfilling regulations in California, where the regulatory agencies have failed to implement regulations that were originally adopted in the 1970s and readopted in 1984, which require that the siting, design, operation, closure and postclosure care (monitoring and maintenance) of a landfill prevent groundwater pollution for as long as the wastes in the landfill will be a threat. These regulations also apply to the Subtitle D landfills that have been developed in the state since the mid-1990s. As Lee and Jones-Lee (2006a) discuss, while these regulations have been in effect since the mid-1980s, they are still not properly implemented by the Regional and State Water Resources Control Boards, with the result that landfills have been and continue to be developed in the state that will eventually pollute groundwaters by landfill waste components. As discussed herein, this same problem exists in the federal and many state landfilling regulations governing the landfilling of municipal solid waste.

Subtitle D Landfill Design Will Not Protect Groundwater for as Long as Leachate Can Be Generated

A typical Subtitle D landfill is designed with a composite liner system composed of a two-foot-thick clay liner and a 60-mil-thick plastic sheeting geomembrane liner. Overlying this composite liner is a leachate collection system consisting of a series of six-inch or so perforated pipes draining to sumps along the exterior of the landfill. The drainage layer will be a porous material such as geonet with a geotextile attached to the top of the geonet. The authors have participated in a landfill permitting hearing where the regulatory agency staff stated, as part of an attempt to convince the public of the safety of the landfill, that the liner that had been proposed and that the regulatory agency had accepted would be "five feet thick." Such a characterization of a minimum Subtitle D liner is highly misleading with respect to its key components for preventing leachate generated in the landfill from passing through it into the underlying groundwater system. In fact, the low-permeability layer of this liner is 60 mil thick (60 thousandths of an inch, which is less than a sixteenth of an inch) – i.e., about the thickness of thin paperboard. With increasing frequency, landfill developers are using a geosynthetic clay liner (GCL) as a substitute for the two feet of clay. While the geosynthetic clay liner is somewhat thicker than the plastic sheeting geomembrane layer, it is only about a quarter-inch thick. The other components included in the five-foot-thick "liner" are a drainage layer and a layer of soil that is designed to separate the drainage layer from the wastes and protect its underlying plastic sheeting liner from puncture by the waste components. As discussed below, the low-permeability components of the liner would not be expected to prevent leachate from passing through them for as long as the wastes in the minimum Subtitle D landfill will be a threat.

Title 40 PART 258--CRITERIA FOR MUNICIPAL SOLID WASTE LANDFILLS-Subpart D--Design Criteria Sec. 258.40 Design criteria states,

> "*(a) New MSWLF units and lateral expansions shall be constructed:*
>
> *(1) In accordance with a design approved by the Director of an approved State or as specified in Sec. 258.40(e) for unapproved States, The design must ensure that the concentration values listed in Table 1 of this section will not be exceeded in the uppermost aquifer at the relevant point of compliance, as specified by the Director of an approved State under paragraph (d) of this section, or*
>
> *(2) With a composite liner, as defined in paragraph (b) of this section and a leachate collection system that is designed and constructed to maintain less than a 30-cm depth of leachate over the liner.*
>
> *(b) For purposes of this section, composite liner means a system consisting of two components; the upper component must consist of a minimum 30-mil flexible membrane liner (FML), and the lower component must consist of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than $1x10^{-7}$ cm/sec. FML components consisting of high density polyethylene (HDPE) shall be at least 60-mil thick. The FML component must be installed in direct and uniform contact with the compacted soil component.*"

As discussed below, the US EPA's assuming that a single composite liner will provide the same degree of protection of offsite groundwater quality as the appropriate monitoring of groundwater at the point of compliance for groundwater monitoring is one of the most significant errors made in developing Subtitle D regulations.

Expected Performance of Subtitle D Landfill Liner System. Lee and Jones-Lee (2004a) have discussed the characteristics and expected performance of the typical Subtitle D landfill liner containment system and monitoring system. As discussed, it is possible to construct a single composite landfill liner system that will not leak leachate at the time of construction at a sufficient rate to pollute large amounts of groundwaters. However, ultimately the plastic sheeting layer of such a landfill liner will deteriorate to the point where it will be ineffective in collecting leachate to enable its removal from the landfill in the leachate collection/removal system. This deterioration will eventually allow transport of leachate through the liner on its way toward the groundwater resources hydraulically connected to the landfill through a vadose (unsaturated) zone, which could be used for domestic water supply purposes. Further, compacted soil (clay layers) used in landfill liners are well-known to experience increased permeability with time over that which was designed and originally constructed.

Lee and Jones (1992) and Lee and Jones-Lee (1998a) have presented reviews of the literature on what is known about the properties of plastic sheeting flexible membrane liners (FMLs) and clay liners with respect to their ability to prevent landfill leachate from passing through them for as long as the wastes in the landfill will be a threat. Peggs (1998) has discussed the inevitable failure of plastic sheeting layers used in landfill covers and liners. Shackelford (1994) has presented a comprehensive review of the potential for waste and compacted soil interactions that alter the hydraulic conductivity of liners. Table 1 summarizes some of the causes of landfill plastic sheeting and clay liner failure.

Table 1
Causes of Liner Failure

Plastic Sheeting FMLs	Soil/Clay Liners
Holes at Time of Liner Construction	Desiccation Cracks
Holes Developed in Waste Placement	Differential Settling Cracks
Stress-Cracks	Cation Exchange Shrinkage (for Expandable-Layer Clays)
Free-Radical Degradation	Inherent Permeability
Permeable to Low-Molecular-Weight Solvents – Permeation	Interactions between Leachate and the Clays
Inherent Diffusion-Based Permeability	
Finite Effective Lifetime – Will Deteriorate and Ultimately Become Non-Functional in Collecting Leachate and as a Barrier to Prevent Groundwater Pollution	Highly Permeable – Allow Large Amount of Leakage under Design Conditions and Subject to Cracking and Other Failure Mechanisms

<u>Liner Failure Inevitable</u>. Hsuan and Koerner (1995) have reported on the initial phase of long-term (10-year) studies underway at that time devoted to examining the rates of deterioration of flexible membrane liners. The focus of the Hsuan and Koerner work was on the breakdown of the polymers in the plastic sheeting liners. They predicted that such breakdown will occur due to free radical polymer chain scission in 40 to 120 years. These estimates were indicated by

Koerner to consider only some of the mechanisms that could cause breakdown. It is possible that breakdown could begin much earlier. Even if the breakdown of the plastic sheeting polymers took 100 years or so, ultimately the plastic sheeting in the flexible membrane liners will break down, leading to an inability to prevent large amounts of leachate from passing through the liner, causing groundwater pollution in the landfill area.

One of the approaches used by Koerner and his associates in an attempt to predict long-term stability of HDPE plastic sheeting liners is the application of the Arrhenius equation. This equation is used in physical chemistry to relate the effect of temperature on the rates of reactions. In some of Koerner's publications he has made predictions in which he has estimated, using the Arrhenius equation and short-term elevated temperature liner deterioration studies, that the HDPE liners should be serviceable for hundreds to a thousand or so years, but eventually will break down. The US EPA (Bonaparte et al., 2002) has released a report that claims that a single composite landfill liner can be expected to have a service life of "1,000 years." A critical review of the technical base for this estimate shows that it is based on an Arrhenius equation extrapolation of a few studies on liner stability that were conducted for short periods of time at elevated temperatures compared to landfill temperatures. This approach for extrapolation is highly speculative and likely to be unreliable. That report continues to support the US EPA (1988a,b) conclusion about the eventual failure of the landfill liner system and its leading to groundwater pollution. While the length of time that the landfill liner will delay groundwater pollution is unknown, there is no doubt that a single composite landfill liner system will eventually fail, and groundwater pollution will occur, when the landfill is sited at locations where there is high-quality groundwater underlying the landfill.

In the US EPA (Bonaparte et al., 2002) report, Koerner made a significant error in claiming that the municipal solid wastes in a Subtitle D dry tomb landfill will only be a threat for about 200 years. There is no technical validity for that estimate. It is obvious that in a "dry tomb" landfill, a number of the normal components of MSW will be a threat forever – not just 200 years. The metals, salts, and many organic compounds that are typically present in MSW and that produce hazardous and deleterious leachate will be a threat forever. In that report the US EPA is attempting to support the continued use of single composite lined landfills for MSW management by claiming the wastes will be a threat for only 200 years, and the liner will work perfectly for 1,000 years. Such claims are fundamentally flawed.

Needham et al. (2003) reported on a study commissioned by the Environment Agency of the UK on the long-term service life of HDPE geomembrane liners. They concluded that,

> " *the service life of HDPE liners depends upon the rate of generation of holes in the liner and the acceptability of leachate or gas leakage at a particular site. A thorough review of physical damage, material degradation processes and the development of holes by stress cracking has been undertaken. A conceptual model of hole generation in six stages throughout the service life of an HDPE liner is presented. Electrical leak location surveys are seen to be effective means of identifying holes caused by physical damage during liner installation and waste disposal, and permitting their repair. Degradation of the HDPE liner is controlled by the liner exposure conditions, the activation energy of the antioxidant depletion process and the oxidative resistance of the material. Where the*

liner is subjected to long-term stresses, stress cracking will lead to the development of holes, and the rate of cracking will increase once oxidation of the liner commences."

Rowe et al. (2003) have reported on the failure of an HDPE lined leachate lagoon. They stated,

> *"A geomembrane – compacted clay composite liner system used to contain municipal solid waste (MSW) landfill leachate for 14 years is evaluated. Field observations of the geomembrane revealed many defects, including holes, patches, and cracks.*
>
> ***
>
> *"Contaminant modelling of the entire lagoon liner suggests that the geomembrane liner most likely stopped being effective as a contaminant barrier to ionic species sometime between 0 and 4 years after the installation."*

It is evident that under some situations there can be rapid failure of HDPE liners that are used in waste management including landfill leachate lagoons and liners.

Minimum Subtitle D landfills include a composite liner composed of a flexible membrane liner (FML) (plastic sheet) and a compacted soil layer or geosynthetic clay liner below it. While in concept a composite liner can provide greater postponement of leakage than the sum of the two liner components, the true composite character is difficult to achieve in practical applications (Lee and Jones, 1992), since it requires that the plastic sheeting liner be in intimate contact with the compacted soil layer. There are significant problems in achieving this degree of contact in the construction of a composite liner.

The clay layer beneath the FML is compacted to achieve a prescribed initial design permeability, which means that even when new, the soil/clay layer will transport leachate at the design permeability. Workman and Keeble (1989) discussed the time it takes leachate to breach a clay layer used as a liner. Through Darcy's Law calculations it is found that a compacted soil layer provides only a short-term slowing of the leakage of leachate through the liner; one foot of clay compacted to 10^{-7} cm/sec permeability, with 0.1 foot of head, will be breached in less than five years. There is increasing evidence that, in addition to general permeability, such liners leak through imperfections that are created at the time of liner construction. Further, compacted clays used as liners are subject to desiccation cracking, cation exchange shrinking, cracking due to differential settling, impacts of chemicals, etc., creating additional points through which leachate can leak, and allowing transport of leachate through the liner at a rate greater than would be expected based on the design permeability.

<u>Desiccation Cracking of Liner</u>. The desiccation cracking of clay liners arises from the fact that in order to achieve the design permeability it is necessary to add water to the clay to typically achieve slighter wetter than optimum moisture density. In time, however, due to unsaturated transport of the water added to the clay, the clay can dry out, leading to shrinkage and desiccation cracks. This situation is readily observed in some soils, where during periods of low precipitation, soils will crack.

<u>Cation Exchange-Related Failure</u>. Some types of clays used in landfill liners, with an expandable lattice structure, exhibit strong shrink/swell properties dependent on the type of

cation on the clay's ion exchange sites. With sodium at the exchange site, the clay is in a swollen state. However, in contact with water with high calcium/magnesium compared to sodium concentrations, the calcium and magnesium will replace the sodium on the clay, and the clay will shrink, leading to higher permeability and possible failure through cracking. Auboiroux et al. (1999) have investigated the impact of calcium exchange for sodium in bentonite geosynthetic clay liners for landfills. They stated, "*Results suggest that while GCL's may be considered as useful materials for reinforcing compacted clay layers at the base of landfills, they should not be considered as "equivalent" to compacted clay layers, at least in terms of pollutant breakthrough times.*" Guyonnet et al. (2005) reported that,"… *calcium carbonate in the bentonite, formed during activation of the calcium bentonite, may redissolve during contact with a dilute permeant, releasing calcium ions that exchange with sodium in the clay. This exchange leads to obliteration of a so-called "gel" phase ~beneficial in terms of low permeability and to the development of a more permeable "hydrated-solid" phase.*" James et al. (1997), in a study of the use of a GCL as a liner to enhance the cover over a reservoir, reported that, "*The evidence demonstrates that calcium from calcite, contained in the GCL bentonite, exchanged with sodium and, in so doing, contributed to shrinkage and cracking.*"

Jones-Lee and Lee (1993) presented a summary of the concentrations of various ions present in leachates from 83 US landfills. The data show that some MSW leachates have higher concentrations of calcium than sodium. In fact, the overall average calcium concentration for all of the landfill leachates investigated was higher than the sodium concentration. This means that, for some compacted clay liners, the low advective permeability (rate of penetration) at the time of installation of the liner will increase as the sodium on the clay is replaced by calcium and the clay shrinks from its original characteristics at the time of construction. This shrinking can lead to ion exchange cracking of the compacted clay liner.

Desiccation cracking and ion exchange cracking of compacted clay layers in a composite liner have been known about since the late 1980s. However, neither the US EPA (2001a) nor state regulatory agencies have adequately considered these issues in evaluating the prospective performance of a single composite liner. Both of these phenomena can lead to a much more rapid rate of leachate penetration through the composite liner than is typically assumed.

Permeation through the Liner. The plastic sheeting HDPE liner will allow dilute solutions of organic solvents such as those that can be purchased in hardware stores for household use to pass through an intact (no holes) liner. Many of these solvents are carcinogens and can be readily transported through groundwater systems. The phenomenon in which organics pass through intact plastic sheeting layers is known as permeation and has been recognized in the landfill liner literature since the late 1980s (Haxo and Lahey, 1988). This is a chemical transport process in which low molecular weight organics dissolve into the plastic liner and exit on the downgradient side. Sakti et al. (1991) and Park et al. (1996), at the University of Wisconsin, Madison, have reviewed the available information on permeation of landfill liners by solvents and have conducted extensive research on it. They found that an HDPE liner would have to be over three inches thick to prevent permeation of certain organics through it for a period of 25 years. Buss et al. (1995) reviewed the information on the mechanisms of leakage through synthetic landfill liner materials. They discussed the importance of permeation of organics through plastic sheeting liners as a landfill liner leakage mechanism that does not require deterioration of the liner properties for leakage to occur. The US EPA and other regulatory agencies continue to ignore this mechanism of landfill liner leakage. There is need to address this issue as part of recommending a single composite liner system for municipal solid waste landfills.

Diffusion Can Be Important. Daniel and Shackelford (1989) have reviewed the inherent leakage rates of plastic sheeting layers and clay liners. They point out that even though plastic sheeting layers can have low permeabilities to water on the order of 10^{-12} cm/sec, compared to clay liners which have a permeability of about 10^{-7} cm/sec at the time of construction, the thin layer of plastic that is used, coupled with its inherent chemical diffusion coefficients, cause plastic sheeting liners of the type used in Subtitle D landfills to have diffusion-controlled breakthrough times for waste components of about two to three years. The clay liner, however, in the landfill cells would be expected to have diffusion-controlled breakthrough times of about 10 years.

Johnson et al. (1989) investigated the rate of penetration of chloride and volatile organic compounds derived from a hazardous waste landfill in vertical cores of an "impervious, unweathered, water-saturated clay." They found that the downward transport of these chemicals into the clay was the result of Fickian diffusion. They state that,

> *"For liners of typical thickness (~1 m), simple diffusion can cause breakthrough of mobile contaminants in approximately 5 years; the diffusive flux of contaminants out of such liners can be large."*

The diffusion of solid waste components through plastic sheeting liners discussed by Daniel and Shackelford occurs through a different mechanism than the permeation of organic solvents (VOCs) through HDPE liners discussed herein. As stated by Daniel and Shackelford (1989), *"No material is impervious, and the question of which liner is more effective, like most questions, is ultimately related to one of economics and the realities of construction practices."* Basically, regulatory agencies, such as the US EPA which has set the national landfilling minimum standard, have been adopting landfill liner systems that will, in time, obviously fail to prevent groundwater pollution. The US EPA stated this fact in its 1988 discussion of the ultimate failure of composite liners as quoted above.

Guyonnet et al. (2001) have discussed that the current approaches to defining clay liner equivalency based on travel times do not adequately consider the magnitude of a disposal site's potential impact on groundwater resources. They emphasized that "... *conclusions relative to the superiority of one multi-layered barrier with respect to another should not only consider hydro-dispersive aspects, but also other processes such as the mechanical and chemical evolutions of the different barrier components. Although such phenomena are poorly addressed by existing models, failure to take them into account, at least in a qualitative fashion, may lead to unconservative conclusions with respect to barrier equivalence."*

Potential Problems with Geosynthetic Clay Liners. Some landfill developers propose to use a single composite liner for the landfill with a 60 mil HDPE plastic sheeting layer and geosynthetic clay layer. While some states allow the substitution of a geosynthetic clay layer for the two feet of clay specified in US EPA Subtitle D regulations, such practice can allow more rapid failure of the composite liner than if the two feet of compacted clay had been used. The US EPA (2001a) has reviewed the properties of geosynthetic clay liners, where a number of the potential advantages and potential problems with substituting a geosynthetic clay liner for two feet of compacted clay have been discussed. A key problem with geosynthetic clay liners is that they are so thin that they have limited structural integrity and will allow rapid penetration of leachate through the liner by diffusion. While landfill applicants and their consultants, and unfortunately some regulatory agencies, will claim that the permeability of a geosynthetic clay liner of 10^{-9} cm/sec under one foot of head will control the rate of leachate passing through the liner, in fact, because of diffusion, leachate can pass through more rapidly. In addition, as discussed above, cation exchange-related shrinkage of the bentonite in the geosynthetic clay layer can lead to higher permeability and possible failure through cracking.

Leachate Collection and Removal System Problems. The key to preventing groundwater pollution by a dry tomb landfill, or, for that matter, by a leachate recycle (so-called "bioreactor") landfill, is the ability to collect all leachate that is generated in the landfill in the leachate collection and removal system. Such systems, to the extent that they function as designed, can reduce the total amount of pollution of groundwaters by leachate generated in a landfill. This is particularly important during the time that the landfill is open to the atmosphere, and precipitation that falls on the landfill becomes leachate. Leachate collection and removal systems, however, as currently designed, are subject to many problems. In principle, leachate that is generated in the solid waste passes through a filter layer underlying the waste which is supposed to keep the solid waste from infiltrating into the leachate collection system (see Figure 1). The leachate collection system consists of gravel or some other porous medium, which is designed to allow leachate to flow rapidly to the top of the HDPE liner. Once it reaches the sloped liner, it is supposed to flow across the top of the liner to a collection pipe, where it will be transported to a sump, where the leachate can be pumped from the landfill. According to regulations, the maximum elevation (depth) of leachate ("head") in the sump is to be no more than one foot. However, leachate collection systems are well known to be prone to plugging. Biological growth, chemical precipitates, and "fines" derived from the wastes all tend to cause the leachate collection system to plug. This, in turn, increases the head of the leachate above the liner upstream of the area that is blocked. While there is the potential to back-flush some of these systems, this back-flushing will not eliminate the problem.

The basic problem with leachate collection systems' functioning as designed is that the HDPE liner, which is the base of the leachate collection system, develops cracks, holes, rips, tears, punctures or points of deterioration. When the leachate that is passing over the liner reaches one of these points, it starts to pass through the liner into the underlying clay layer. If the clay layer is in intimate contact with the HDPE liner, the rate of leakage through the clay is small. If, however, there are problems in intimate contact between the clay and HDPE layers, such as a fold in the plastic sheeting, then the leakage through the hole in the HDPE layer can be quite rapid. Under these conditions, the leachate spreads out over the clay layer and can leak at a substantial rate through the clay.

The theoretical rate of leakage through a clay liner, if it is constructed properly and has, at the time of construction, a permeability of 10^{-7} cm/sec with 1 ft of head, is about 1 in/yr. Therefore, since the clay liner should be a minimum of 2 ft thick, leachate in the areas of the liner where there is 1 ft of head will penetrate through holes in the HDPE and then through the clay liner in about 25 years. There are several reasons, however, why the penetration through the clay liner could be much more rapid. These include desiccation cracking of the clay associated with the vadose zone transport of the moisture that is used to achieve optimum moisture density at the time of clay liner construction, which moves by gravity out of the clay into the underlying strata.

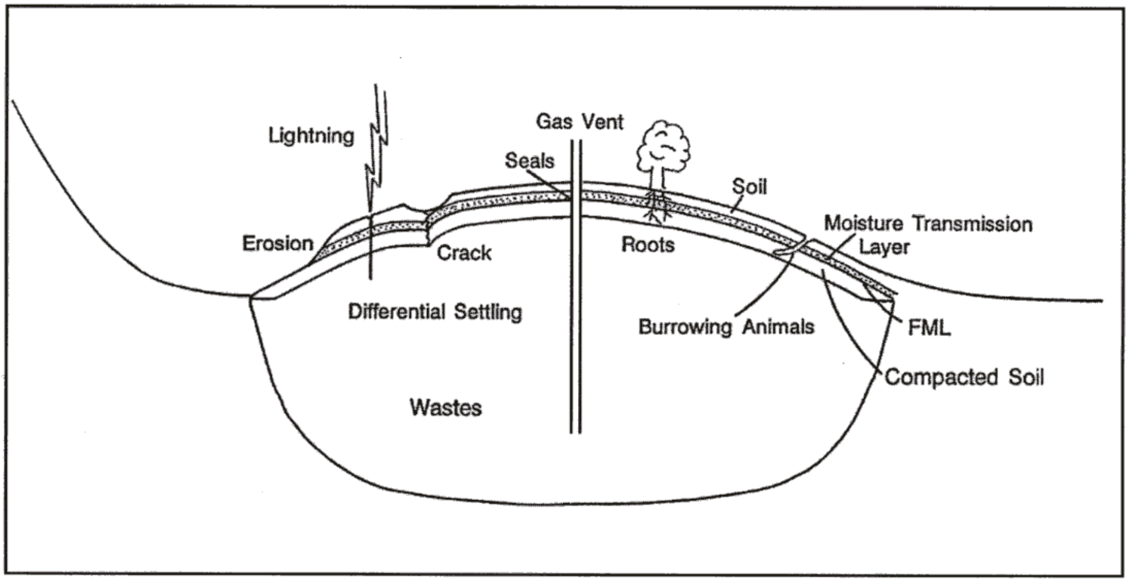
Plugging of Leachate Collection Systems. An issue that is not adequately addressed in landfill applications is that municipal landfill leachate is well-known to cause plugging of the leachate collection and removal system, thereby allowing greater than one foot of head on the liner on the upgradient side of the plugged area. This plugging arises from chemical precipitation and biological growths. The buildup of head (leachate depth) on the liner leads to greater rates of leakage than would occur if the depth of leachate were less than the one foot allowed in Subtitle D regulations. While some landfill owners and their consultants claim that they can clean out the leachate collection system and thereby eliminate any plugging, in fact such cleaning can only partially address the plugging problem. Further, this plugging problem will continue long after the end of the 30-year mandatory postclosure care period when leachate collection system clean-out could potentially be implemented.

It is appropriate to conclude that landfill liners of the type proposed for a minimum Subtitle D landfill, while possibly providing short-term protection of groundwater quality, are not reliable for long-term protection and will ultimately fail to prevent leachate from passing through them. This will result in pollution of groundwater underlying and downgradient from the landfill area, rendering the groundwater unusable for domestic and many other uses.

Unreliable Evaluation of the Long-Term Integrity of Landfill Covers. Subtitle D landfills are allowed to be closed with a landfill cover consisting of a soil layer above the wastes shaped to serve as the base for a low-permeability plastic sheeting layer, which is overlain by a one- to two-foot-thick drainage layer (Figure 1). Above the drainage layer is a few inches to a foot or so of topsoil that serves as a vegetative layer. The vegetative layer is designed to promote the growth of vegetation that will reduce the erosion of the landfill cover. In principle, this landfill cover is supposed to allow part of the moisture that falls on the vegetative layer of the landfill to penetrate through the root zone of the vegetation in this layer to the porous (drainage) layer. When the moisture reaches the low-permeability plastic sheeting layer, it is supposed to move laterally to the outside of the landfill.

Landfill permit applicants and their consultants as well as some regulatory agency staff will claim that the eventual failure of the landfill bottom liner system is of limited significance in leading to groundwater pollution, since the landfill cover can keep the wastes dry, and thereby prevent leachate generation. Landfill permit applicants and their consultants, as well as some governmental agency staff who support a single composite liner system, will, at permitting hearings, show a picture of landfill leachate generation once the landfill is closed with a low-permeability cover. This image shows that the leachate generation rate in the closed landfill is greatly curtailed within a year after the cover is put in place. While they would like to have others believe that this situation will continue to exist in perpetuity, it will not, because of the eventual deterioration of the low-permeability plastic sheeting layer in the landfill cover. This issue is discussed further below. Figure 2 presents the various processes that can affect the integrity of landfill covers.

Figure 2
Factors Affecting Landfill Cover Integrity



Another deception with respect to landfill covers is that they can be effectively monitored to detect when moisture leakage through the cover occurs. The typical monitoring approach that is advocated by landfill owners and operators and allowed by regulatory agencies involves a visual inspection of the surface of the vegetative soil layer of the landfill cover. However, as discussed by Lee and Jones-Lee (1995a, 1998a, 2004a), since the low-permeability layer (plastic sheeting) is buried below topsoil and a drainage layer, it is not possible to detect when the plastic sheeting layer deteriorates sufficiently to allow moisture that enters the topsoil and drainage layer to pass into the landfilled wastes. Distressed vegetation on the cover is not reliable for detection of plastic sheeting layer failure. If cracks or depressions are observed in the topsoil layer, these are filled with soil. Such an approach will not detect cracks in the plastic sheeting layer. As a result, the moisture that enters the drainage layer, which comes in contact with the plastic sheeting layer and which, when the plastic sheeting is new and constructed properly, runs off of the landfill, will instead penetrate into the wastes. This could occur at any time during the postclosure care period, and the increased leachate generation would be detected. However, it could also readily occur in year 31 after closure or thereafter, when there could be no one monitoring leachate generation, collection and removal.

Unless the landfill owner agrees to install, operate, and maintain in perpetuity a leak-detectable cover for the landfill, the landfill cover system will fail to prevent entrance of moisture into the landfill and generation of leachate, even if it meets minimum Subtitle D requirements that are typically accepted by regulatory agencies. The leachate will, in turn, pass through the deteriorated bottom liner system into the underlying groundwaters.

Further, even if failure of the landfill cover were detected, the typical postclosure funding that is allowed does not provide adequate funds to determine the location in the low-permeability layer of the landfill cover that has failed and to repair it. In developing the amount of required postclosure funding, it is assumed by the regulatory agencies that the low-permeability plastic sheeting layer in a dry tomb landfill cover will maintain its integrity throughout the 30-year postclosure care period, even though it is understood that the plastic sheeting layer in a landfill cover is subject to significant stresses due to differential settling of the wastes that can lead to its failure to prevent moisture from entering the wastes.

Leak-Detectable Covers**.** The high probability of failure of the low-permeability layer of the landfill cover is the reason why Lee and Jones-Lee (1995a) advocate the use of leak detectable covers on landfills, which are operated and maintained in perpetuity – i.e., as long as the wastes are a threat. This approach requires that a dedicated trust fund be developed that is of sufficient magnitude to ensure that, at any time in the future while the wastes are still a threat (typically, forever), the leaks in the cover can be isolated and repaired.

This long-term financial commitment to maintaining a low-permeability cover on the landfill would significantly increase the cost of solid waste management. This is the political reason that regulatory agencies, from the US EPA through the state agencies, do not implement the dry tomb landfilling approach so that it addresses the long-term problems associated with this landfilling approach. Until this issue is meaningfully addressed, today's dry tomb landfills at best are façades with respect to their ability to protect public health and the environment from landfilled wastes for as long as the wastes in the landfill will be a threat.

The situation is that no political entity – from the federal administration in power through the federal Congress, state governors and legislatures, to county Boards of Supervisors – wants to be responsible for causing those who generate solid waste (the public) to pay the true cost of its management/disposal. It is estimated that solid waste disposal that is truly protective of public health and the environment would double to triple the cost of solid waste management. Instead of increasing everyone's cost of solid waste management by 15 to 25 cents per person per day, the political entities are opting for short-term protection, and passing these costs on to future generations in terms of lost groundwater resources and adverse impacts on the health, welfare and interests of those in the vicinity of the landfills.

Alternative Cover Design. Subtitle D regulations require that the landfill cover be no more permeable than the bottom liner. This is typically interpreted to mean that the landfill cover should include a plastic sheeting layer as the low-permeability layer. However, Subtitle D regulations allow alternative cover designs that provide the same degree of control of moisture entering the landfill as a cover that contains a plastic sheeting layer. This alternative approach to cover design requires a demonstration of equivalency to the plastic sheeting based cover. The demonstration of equivalent performance is based on HELP model calculations which purport to show that a proposed soil cover for a landfill will have a permeability that is less than a cover with a plastic sheeting layer.

A critical review of the HELP model calculations shows that a key component of the calculations of the expected amount of percolation of water through the cover into the wastes is the assumed permeability of the low-permeability layer of the cover. Typically, landfill consultants assume that the construction of the cover will achieve the design permeability. Further, and most importantly, they assume that the design permeability of the cover will be maintained over the period of postclosure care (30 years) and throughout the period that the wastes in the landfill will be a threat. However, no information is provided on the permeability of the cover over the period of time that the wastes in the landfill will be a threat – i.e., effectively, forever.

In the late 1980s/early 1990s, the US EPA conducted a series of seminars on RCRA/CERCLA landfill design issues. One of these was devoted to "Design and Construction of RCRA/CERCLA Final Covers" (US EPA, 1990). Included in the seminar notes was a section developed by Dr. David Daniel, then of the University of Texas, Austin (Daniel, 1990), which presented "Critical Factors in Soils Design for Covers." Dr. Daniel, in the appendix to his presentation, presented a paper by Montgomery and Parsons (1989), which summarized the results of a three-year study conducted in cooperation with the state of Wisconsin on the performance of various types of landfill soil covers. The Montgomery and Parsons study was conducted on three different 40ft x 40ft test plots near Omega Hills, Wisconsin, which is near Milwaukee. Daniel (1990) summarized the results, where, after three years,

- *"Upper 8 to 10 in. of clay was weathered and blocky*
- *Cracks up to ½ inch wide extended 35 to 40 inches into the clay*
- *Roots penetrated 8 to 10 inches into clay in a continuous mat, and some roots extended into crack planes as deep as 30 in. into the clay"*

Daniel also discussed the problems with soil/clay covers in withstanding stress-strain relationships associated with differential settling of the wastes under the cover, where he pointed out that differential settling can readily lead to cracks in the soil cover.

It is inappropriate to assume that the design permeability of the soil cover for a landfill will be applicable to controlling the amount of moisture that enters the wastes through the cover for as long as the wastes in the landfill will be a threat. What will actually occur at proposed landfills with alternative landfill covers is that within a few years after construction of the cover the permeability of the cover will increase due to desiccation and differential settling cracks. Over time, vegetation roots will also increase the permeability of the cover. Therefore, the so-called equivalency of the soil cover to the plastic sheeting based cover will no longer hold.

Landfill Cover Area Reuse. Waste Management, Inc. has made substantial claims that its closed landfills make ideal wildlife habitat, and sites for golf courses and public recreation areas including dirt bike trails. Such claims appear in its "Think Green" campaign at http://www.thinkgreen.com/ in its discussion of "Beneficial Land Reuse," as well as in a number of television advertisements. It cites locations at which such reuse has been made of landfill cover areas. The unmistakable implication is that the public should not be concerned about the potential long term threats to public health, groundwater and surface water quality, or to wildlife, at a closed landfill. However, as discussed by Lee and Jones-Lee (1994b) in their paper entitled, "Closed Landfill Cover Space Reuse: Park, Golf Course, or a Tomb?" many of the touted reuse activities atop closed landfills are ill-advised at best, and such implications are highly misleading. One reason for this is that many of the land "enhancements" and activities being promoted stand to damage the integrity of the landfill cover upon which the integrity of the landfill containment system depends. As discussed elsewhere herein, in order to prevent formation of landfill gas and leachate that will eventually escape the landfill containment, the wastes must be kept dry. Placing water features such as ponds, wetlands, idyllic streams, or water hazards on a golf course, or deep-rooted vegetation such as trees and shrubs, atop or in close association with landfill covers promotes entrance of moisture into the cover.

Closing Unlined Landfills. The final closure of unlined sanitary landfills is typically accomplished by installing a base-to-final cover of soil of a few inches to several feet thick. This layer is designed to provide a suitable structural base for the low-permeability layer in the cover. On this layer is placed a 1- to 2-foot-thick compacted soil layer with a permeability, at the time of construction, of 10^{-6} to about 10^{-7} cm/sec. The purpose of this layer is to reduce the penetration of moisture into the landfilled wastes. At some locations, a plastic sheeting layer is used instead of the compacted soil layer as the low-permeability layer in the cover.

On the low-permeability layer is placed a several-foot-thick drainage layer that is covered by a few inches to a foot or so of topsoil. The topsoil layer serves as a base for establishing vegetation that can reduce erosion of the landfill cover. The underlying drainage layer allows moisture, which is needed to keep the vegetation in the topsoil layer alive, to penetrate through the topsoil layer to the low-permeability layer where it can run off on this layer to the sides of the landfill. Basically this approach is a variation of the dry tomb approach, where it is believed that if the moisture supply to the landfilled wastes is curtailed, the rate of landfill gas and leachate generation will be reduced/curtailed.

This approach for final closure of an existing unlined landfill has several of the same problems as the closure of minimum design Subtitle D landfills. Typically regulatory agencies will allow landfill owners and their consultants to make HELP calculations on the rate of water penetration through the compacted soil layer in the cover, where it is assumed that the design permeability of the cover will be applicable to the infinite period of time that the closed landfilled wastes will be a threat to generate leachate upon contact with water. However, it is known that the compacted soil/clay layer in the landfill cover can crack within a short time after installation and allow water that penetrates through the topsoil and drainage layer to enter the landfilled wastes through the cracks in the low-permeability layer. The HELP model calculations of moisture penetration into the closed landfill are unreliable a few years after landfill closure for predicting the moisture that will enter the wastes through the cracked compacted soil layer. This cracking is associated with desiccation of the compacted soil layer associated with loss of the moisture that is used to achieve compaction of this layer as well as drying of this layer during period of no/low precipitation.

If plastic sheeting is used as the low-permeability layer in the cover it will be subject to stress cracking and free radical degradation which can occur at a higher rate than in the bottom HDPE liner typically used at Subtitle D landfills. When this deterioration of the plastic sheeting layer occurs, water that is supposed to be transported off the plastic sheeting layer to the sides of the landfill will penetrate into the wastes and generate leachate. The failure of the compacted soil layer or the plastic sheeting layer in the landfill cover will not likely be visible from the surface of the landfill since it is buried under several feet of topsoil and a drainage layer.

Some landfill owners and their consultants claim, with support by the regulatory agency, that the failure of the low-permeability layer in the closed unlined landfill will be detected by groundwater monitoring. While a few downgradient groundwater monitoring wells normally can readily detect groundwater pollution by unlined landfills, the closed unlined landfills have the same problems of the minimum design Subtitle D landfills, where narrow plumes of leachate will initially be generated associated with the penetration of the water through the low-permeability layer of the cover. Rather than the pollution of groundwater occurring under the whole area of the landfill, the new groundwater pollution in a closed landfill will occur under the areas where the low-permeability layer in the cover fails to prevent water from entering the wastes. Typically a much more extensive downgradient groundwater monitoring well array is needed for a closed unlined landfill than an unlined landfill that does not have a low-permeability layer in the cover. In developing this array, the landfill owner should be required to have a consultant determine the number and location of monitoring wells that will be needed to reliably detect a new leachate-polluted groundwater plume that could arise from cracks and points of deterioration that occur in the low-permeability layer of the cover. This evaluation should consider the site-specific characteristics of the hydrogeology of the area underlying the landfill as well as the potential for leakage from any location in the landfill footprint.

Landfills at Superfund Sites. As part of remediation of Superfund and other hazardous chemical sites, onsite or nearby landfills are sometimes used to store so-called “nonhazardous” wastes. As discussed below, these wastes, while classified by the US EPA as nonhazardous, can readily contain large amounts of known hazardous chemicals that are a threat to human health and the environment. Further, these wastes can contain a large number of unidentified, unregulated hazardous chemicals as a result of the limited approach that is allowed to be used to identify constituents of concern at Superfund sites. Lee and Jones-Lee (2004b) and Lee (2003b) have discussed the potential problems with using onsite and nearby Subtitle D landfills for hazardous chemical site remediation. These are the same problems that occur with Subtitle D landfills for MSW, with the addition that Superfund site onsite landfills often are a greater threat to public health because of the types of wastes that are allowed to be deposited in these landfills.

At some Superfund sites existing waste piles (such as mine tailings) are “remediated” by placing a low-permeability cover over the waste pile. This approach only postpones additional groundwater pollution by the waste pile. Lee and Jones-Lee (2003) have discussed this type of situation for the Lava Cap Mine Superfund site located in Nevada County, California. This site is a former gold mine that has large amounts of mine tailings that contain elevated concentrations of somewhat leachable arsenic. The US EPA, which is the lead agency for this Superfund site investigation, concluded that capping an arsenic containing tailing pile was the most economical method for remediation of this area. However, the economic calculation allowed by the Agency only considered short-term effectiveness of the capping and failed to consider that the tailings in the capped area would be a threat to generate leachate which has arsenic concentrations that are a threat to human and some animal health. The US EPA does not include in its economic evaluation of Superfund site remediation approaches, the eventual failure of the landfill cap and the additional costs of site remediation that will have to be done at some time in the future. Lee and Jones-Lee (2005a) have discussed the need to consider both the short-term and long-term costs and impacts of landfilling of wastes in selecting contaminated site remediation approaches.

A special case of Superfund site remediation approaches is the US EPA’s “Presumptive Remedy” for “remediation” of municipal landfills at Superfund sites. Several years ago, the

Agency adopted the Presumptive Remedy for a MSW landfill at a Superfund site of capping of the landfill with a low-permeability cap. Such a cap is subject to all the issues that are discussed above for capping unlined landfills. This remedy is allowed by the US EPA without determining whether the landfill is polluting groundwater. This approach is another of the short-sighted approaches toward managing solid wastes, where the true long-term costs and impacts are not considered in Superfund site investigation/remediation.

Lee (2006a) discussed the potential problems of allowing the use of the Presumptive Remedy for remediation of three landfills located at the University of California, Davis (UCD)/Department of Energy LEHR national Superfund site located on the UCD campus. Even though the hydrogeology of the strata underlying these landfills is fairly homogeneous and can be readily monitored for landfill liner leakage for landfills that have a soil layer as a cap (i.e., classical sanitary landfills), once a low-permeability cap is installed on the landfill as part of the Presumptive Remedy approach, the ability to monitor groundwater pollution that will occur at some time in the future becomes much more difficult. This is the result of the low-permeability cap allowing water to enter the landfill at limited locations. Under the soil cap approach, the precipitation could enter the landfill essentially at all locations through the cap. With the low-permeability cap, those areas where this cap initially fails to prevent moisture from entering the wastes will generate areas under the landfill where leachate may pass in limited-dimension plumes. These plumes may not intersect with the generally used monitoring well array for groundwater pollution from classical sanitary landfills.

In the 1980s the US EPA and states allowed drummed liquid hazardous waste to be buried in landfills with only a clay liner. At a number of sites it has been found that the regulatory agencies allow a few monitoring wells spaced at considerable distances down groundwater gradient from the drummed waste burial area, thus ignoring the fact that the initial pollution of groundwaters by the liquid hazardous waste will occur from the corrosion of a few drums through limited-dimension plumes that may not intersect with the monitoring wells. This makes monitoring of the initial leakage unreliable using vertical monitoring wells spaced hundreds of feet apart. A possible approach for monitoring of the initial leakage in this type of situation would be through the use of the SEAMIST™ system, in which, through horizontal drilling under the landfill liner, an array of vapor phase monitoring wells can be constructed and monitored to detect hazardous chemicals with an appreciable vapor pressure. Information and an evaluation of this system is available from the US Department of Energy (US DOE, 1995) at http://web.em.doe.gov/plumesfa/intech/seamist/index.html.

Unreliable Groundwater Monitoring

The Subtitle D requirement for groundwater monitoring – *"The design must ensure that the concentration values listed in Table 1 of this section will not be exceeded in the uppermost aquifer at the relevant point of compliance"* – requires that a highly reliable groundwater monitoring system be developed for Subtitle D landfills. The point of compliance for groundwater monitoring can be no more than 150 meters from the groundwater gradient edge of the waste deposition and must be located on the landfill owner's property. In principal, if such a program is developed, then the inevitable failure of the landfill liner system will not lead to offsite groundwater pollution. Landfill developers at landfill permitting hearings frequently state that the proposed groundwater monitoring system for the proposed landfill will be consistent with the groundwater monitoring requirements prescribed under 40 CFR Part 258, §258.51, and has been designed to provide a sufficient number of wells for detection and assessment monitoring. The landfill developer then typically proposes a groundwater monitoring system that consists of several groundwater monitoring wells located at hundreds to a thousand or more feet apart at the point of compliance. A critical evaluation of the potential reliability of this monitoring approach shows that it has a very low probability of detecting leachate-polluted groundwaters when they first reach the point of compliance for groundwater monitoring at minimum Subtitle D landfills.

One of the most significant deficiencies in implementing Subtitle D landfilling regulations is in the permitting of groundwater monitoring systems for the purpose of detecting the inevitable failure of the single composite liner to prevent landfill leachate from passing through the liner into groundwater systems underlying the landfill. Lee and Jones-Lee (1993a, 1998b) presented comprehensive reviews of groundwater quality monitoring issues for Subtitle D landfills. As they pointed out, a fundamental problem with typical groundwater monitoring programs for minimum Subtitle D landfills is that they have been developed based on perceptions of leakage from **unlined** landfills without proper consideration of the manner in which **lined** landfills leak and pollute groundwater. Conventional unlined sanitary landfills are expected to leak leachate over a considerable part of the bottom of the landfill. Therefore, even though the lateral spread of a plume of leachate-contaminated groundwater can be very limited depending on the aquifer characteristics (Cherry, 1990), the plume of leachate-contaminated groundwater in some types of geological/hydrogeological strata would move as a wide front downgradient of the unlined landfill (Figure 3). Under those conditions, well spacing may not be critical for the detection of groundwater contamination by leachate. However, this is not the character of initial leakage from plastic sheeting lined landfills.

Initial Liner Leakage can Produce Narrow Plumes of Leachate-Polluted Groundwater. Bumb et al. (1988) and Glass et al. (1988) discussed that the initial leaking of leachate from lined landfills will occur from point sources in the liners, rather than uniformly from the landfill bottom as may be expected from unlined landfills. The initial leaks will occur from holes, rips, tears and points of deterioration in the plastic sheeting liner. That fact changes the significance to groundwater monitoring of Cherry's (1990) finding that the lateral spread of a plume of leachate-contaminated groundwater is limited. In a study of the lateral dispersion of leachate plumes from lined landfills, Smyth (1991) of the Waterloo Centre for Groundwater Research, University of Waterloo, reported that a 0.6-m (2-ft)-wide point-source tracer spread laterally to a width of only about 2 m (6 ft) after traveling 65 m (213 ft) in a sand aquifer system. Thus, it is clear that leakage from point sources such as holes in liners can move downgradient as narrow "fingers" of leachate (Figure 4) rather than in the traditionally assumed fan-shaped plumes such as shown in Figure 3. This means that conventional wells used for monitoring of the pollution of groundwaters caused by lined landfills must be placed close enough together at the point of compliance to detect narrow fingers of leachate, if the monitoring program is to comply with Subtitle D requirements for the detection of incipient groundwater pollution from waste management units at the point of compliance.

The typical groundwater monitoring well used today has a four- to eight-inch diameter borehole. Such wells are normally purged prior to the quarterly or so sampling, by removal of three to five

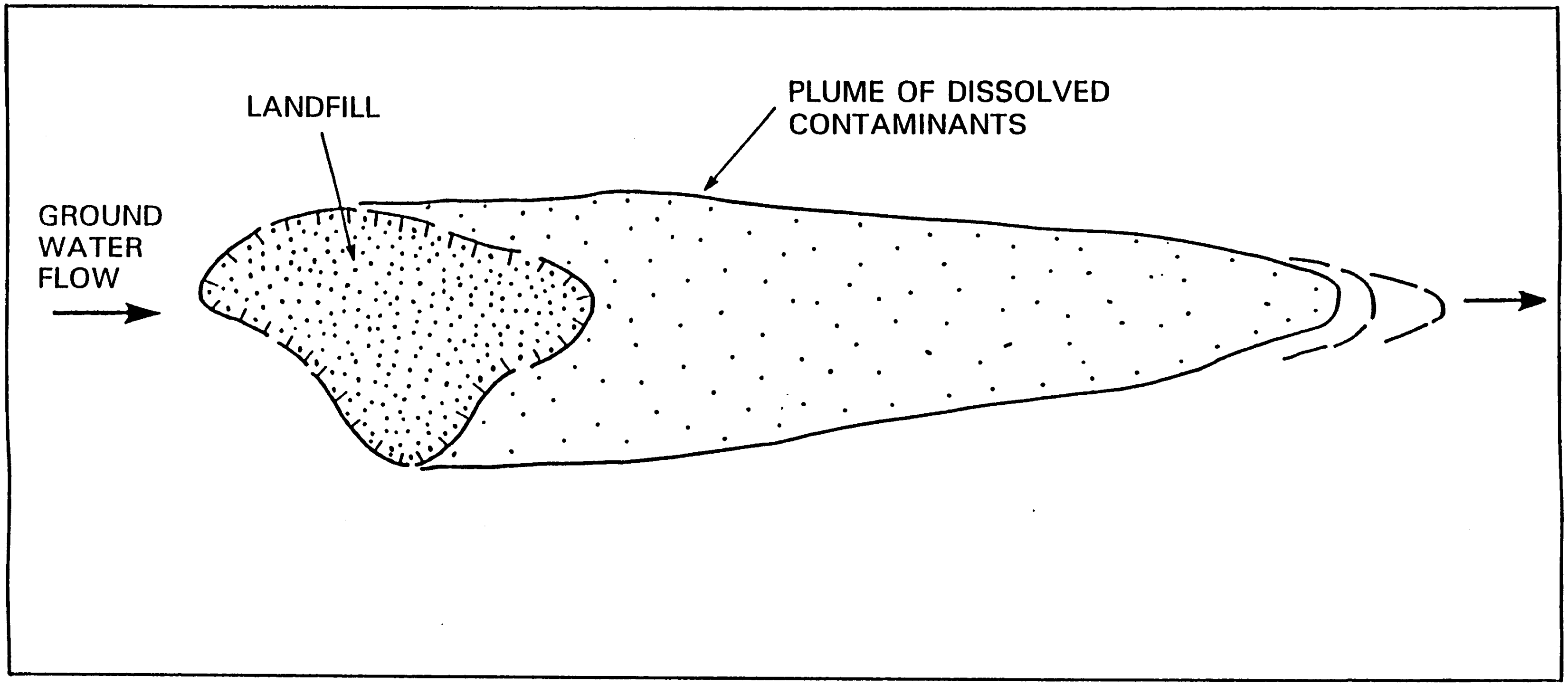


Figure 3. Pattern of Landfill Leakage – Groundwater Contamination from Unlined Landfills
(after Cherry, 1990)

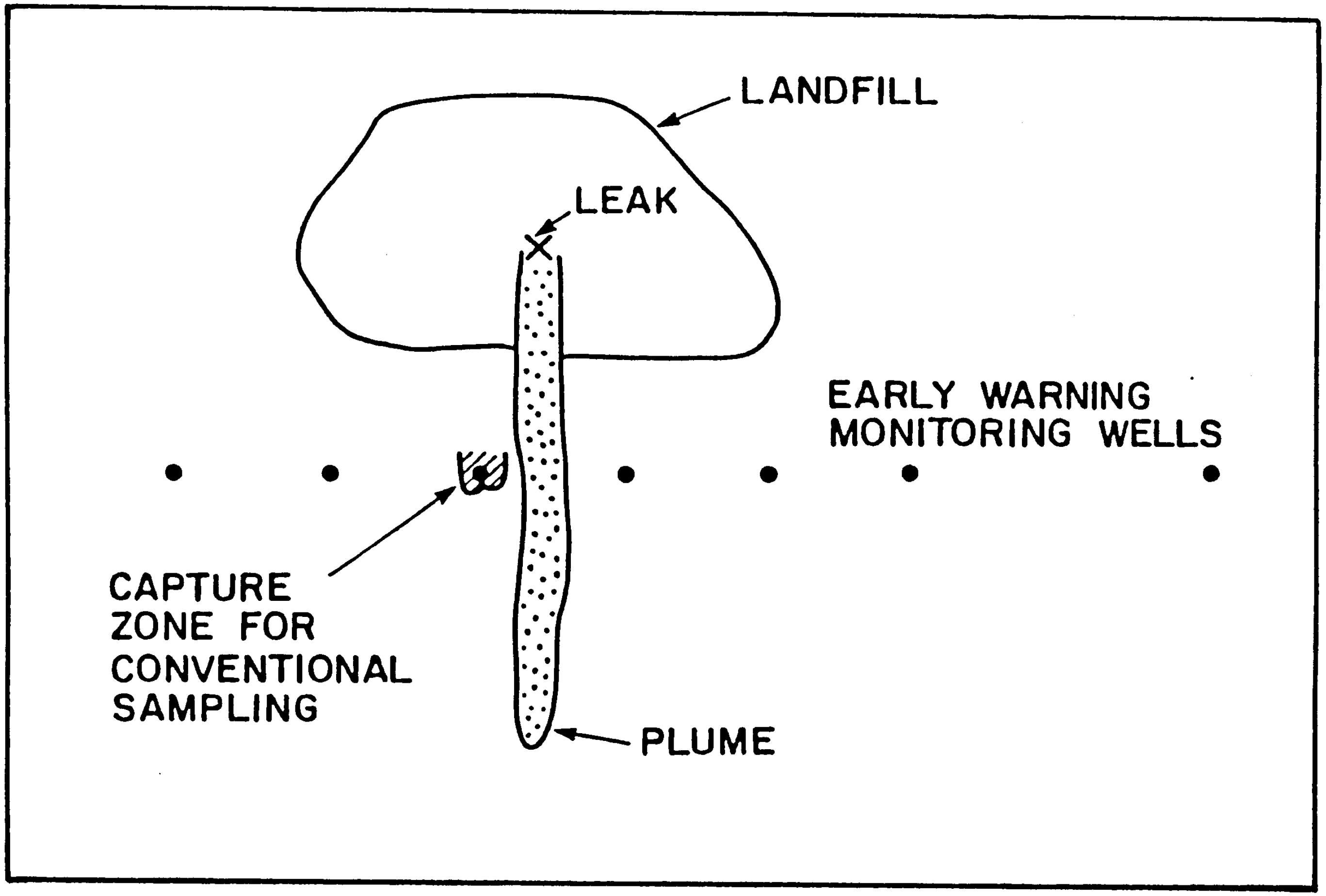


Figure 4. Pattern of Landfill Leakage – Groundwater Contamination from Lined Landfills
(after Cherry, 1990)

borehole-volumes of water. Thus, the zones of capture for such monitoring wells are on the order of a foot around each well. Since the lateral spread of a finger plume of leachate-contaminated groundwater from a lined landfill is dependent on aquifer characteristics and can be minimal, especially for leaks arising on the downgradient edge of the waste deposition area, monitoring wells that are spaced hundreds of feet apart at the downgradient edge of some lined landfills have a low probability of detecting the finger plumes of leachate produced by leaks in the liner system (Figure 4). Those finger plumes of leachate could travel long distances before groundwater pollution by the landfill is detected.

Parsons and Davis (1992) discussed issues of monitoring well spacing and zones of capture of monitoring wells associated with waste management units. As they discussed and as illustrated in Figure 5, in order to have a high probability of detecting leachate leakage from a waste management unit, the spacing of standard monitoring wells at the point of compliance must be such that zones of capture overlap. Thus, in order to be effective in achieving the groundwater monitoring performance standard of Subtitle D, for some landfills, conventional vertical groundwater monitoring wells would have to be spaced no more than a few feet apart along the entire downgradient edge of the landfill, creating a "picket fence" of wells.

On May 14, 2008 the CA Department of Toxic Substances Control (DTSC) and the US EPA held a Remediation Technology Symposium (the agenda for which is available at http://www.dtsc.ca.gov/HazardousWaste/upload/Remediation_Technology_Symposium_Agenda.pdf). At that symposium Einarson (2008) made a presentation entitled, "Site Characterization and Monitoring in the New Millenium," devoted to problems with conventional groundwater monitoring approaches used at hazardous chemical sites. He discussed the fact, as Cherry (1990) had nearly two decades ago, that groundwater pollution plumes emanating from plastic-sheeting-lined landfills tend to have limited lateral spread. Because of this characteristic, groundwater monitoring wells spaced hundreds of feet apart at the point of compliance for groundwater monitoring will have a low probability of detecting groundwater polluted by landfill leachate when it first reaches the point of compliance for groundwater monitoring.

The problems of the unreliability of groundwater monitoring in plastic sheeting lined landfills to detect groundwater pollution before widespread offsite groundwater pollution has occurred are well-recognized. A number of states, including Michigan in its Rule 641, require double composite liners for municipal solid waste landfills (see Figure 6). These liners are similar to those required for hazardous waste landfills. They also require that a leak-detection system be used between the two composite liners to determine when the upper composite liner has failed. This approach, where the lower composite liner is a pan lysimeter for the upper composite liner, is a far more reliable monitoring approach for detecting liner leakage than the single composite liner with wells spaced along the point of compliance. The leachate in each major cell of the landfill should be monitored at least quarterly for the full suite of pollutants. The liquid in the leak detection system under the upper composite liner should be monitored for a suite of typical leachate pollution parameters including the VOCs (low molecular weight solvents). Finding VOCs in the leak detection zone liquid can be an early warning sign of liner failure since these chemicals are highly mobile. VOCs in the leak detection zone liquid is also an indication that the permeation of the HDPE plastic sheeting liner by VOCs is occurring.

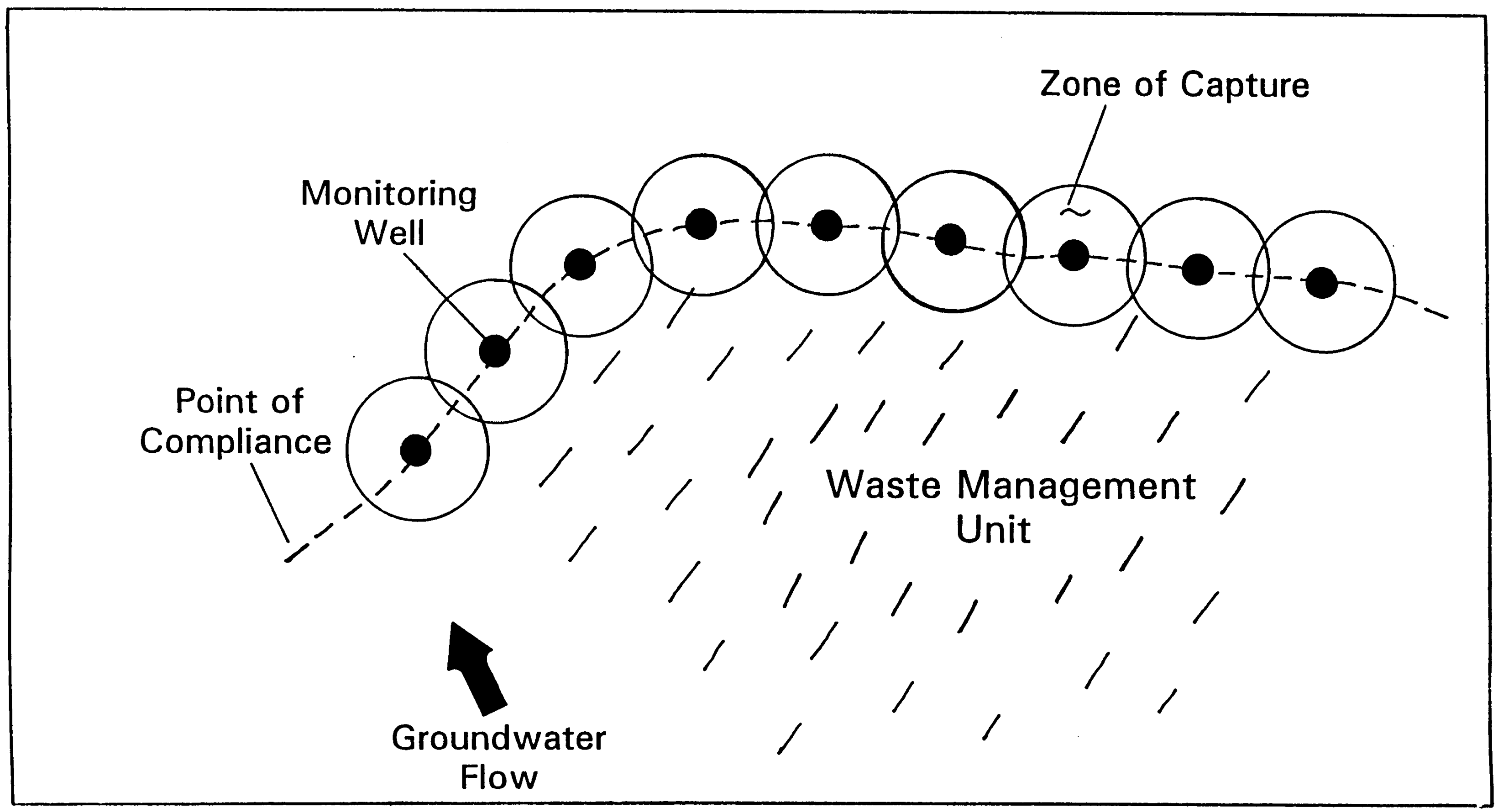
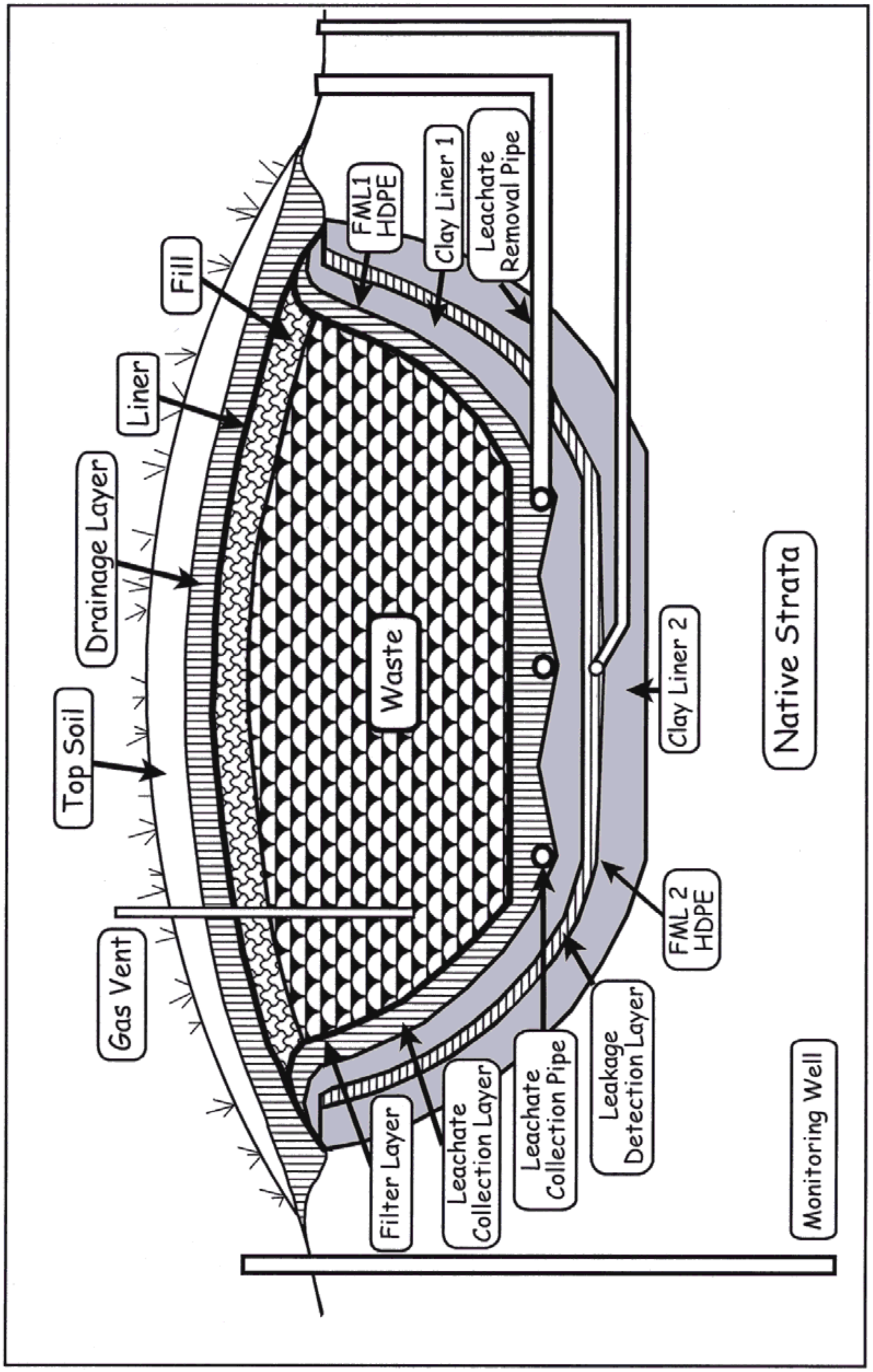


Figure 5. Zones of Capture of Standard Monitoring Wells Must Overlap to Detect Leakage from Lined Landfills (after Parsons and Davis, 1992)

Figure 6
Double Composite Liner Landfill Containment System



Monitoring of Some Fractured Rock Aquifers Nearly Impossible. The ability to define the shape and movement of a contaminant finger-plume from a lined landfill depends on the hydrogeological characteristics of the aquifer-strata. In homogeneous, isotropic "sand" systems, the vertical and horizontal spread of point source discharges/leaks from a given point can be estimated with some degree of reliability. However, the hydrogeology of many locations in which landfills are sited is sufficiently complex so that predictions of the spread of a leachate plume are fairly unreliable. The presence of fractured bedrock, fissures, cavernous calcareous strata, and non-isotropic lenticular aquifers (such as former river beds) make the reliable prediction of flow paths from point-source leaks from lined landfills more difficult or even impossible and make the monitoring of groundwater for incipient leachate pollution highly unreliable and virtually impossible. Haitjema (1991) stated,

> *"An extreme example of Equation (1) (aquifer heterogeneity) is flow through fractured rock. The design of monitoring well systems in such an environment is a nightmare and usually not more than a blind gamble."*
>
> * * *
>
> *"Monitoring wells in the regional aquifer are unreliable detectors of local leaks in a landfill."*

Even the fact that a monitoring well intercepts a fissure/crack does not mean that the leachate in that fissure system is reliably sampled during groundwater monitoring. The amount of water extracted during sampling is typically quite small; the result is that the zone of capture around the monitoring well, even in a fracture, is often limited. Thus, leachate-contaminated groundwater can be present in a fracture without its being detected by the monitoring programs typically used. Therefore, in addition to misconceptions about the nature of the spread of leachate from lined landfills, an incomplete or unreliable assessment of the geological features of the subsurface system and complex hydrogeology can further reduce the probability that the groundwater monitoring well array will intercept any initial plume of leachate-contaminated groundwater at the point of compliance for the MSW landfill monitoring program. This situation raises significant questions about whether single composite lined landfills should be allowed to be located above fractured rock aquifer systems, because of the inability to reliably monitor groundwater pollution in such systems.

Lee and Jones-Lee (2006a, 2007a), in their Groundwater Quality Protection Issues review, summarized their experience in investigating the potential impacts of landfills that are underlain by a fractured rock or fractured clay aquifer system. This is a fairly common situation, which can readily lead to groundwater pollution that cannot be reliably monitored. An example of this type of situation occurred under the Sydney Tar Ponds in Sydney, Nova Scotia, Canada. Lee and Jones-Lee (2006b) and Lee (2006b,c,d) have discussed the situation that has developed where about 100 years of steel-making with essentially no pollution control led to pollution of the estuarine sediments near Sydney, Nova Scotia, with PAHs, PCBs and a variety of other pollutants. It is estimated that to remediate this situation will require about

$400 million. One of the problems at this site is that it is underlain by fractured rock, where in some areas there is flow from the fractured rock into the sediments, and in others, there is flow from the polluted sediments into the fractured rock. The latter provides a pathway for pollutants to pass from the sediments under any barriers that are constructed above the fractured rock, and eventually pollute the estuarine waters downstream of the barriers. Additional information on this situation is available on the Sierra Club of Canada's website, www.safecleanup.com.

Regulatory Agency Staff Should Evaluate Ability of Groundwater Monitoring System to Detect Initial Groundwater Pollution. Landfill groundwater monitoring systems based for a single composite liner based on vertical monitoring wells located more than a few feet apart at the point of compliance for monitoring is best characterized as "cosmetic" with respect to reliable detecting groundwater pollution by landfill leachate when it first reaches the point of compliance for monitoring. It is recommended that regulatory agencies, as part of the permitting of a proposed landfill, conduct a site-specific evaluation of the ability of the proposed monitoring well array to detect leachate-polluted groundwaters at the point of compliance all along the downgradient edge of the landfill from leaks that occur from holes, rips, tears or points of deterioration in the HDPE liner. In making this evaluation it should be assumed that the leak would occur through a two-foot long area at any point in the landfill footprint, including especially near the downgradient edge of the landfill.

Further, the regulatory agency should determine the spacing of vertical monitoring wells at the point of compliance that should occur in order to have at least a 95 percent probability of detecting such leaks when they first reach the point of compliance for groundwater monitoring. Conducting such an evaluation for most Subtitle D landfills will show that the proposed monitoring well array along the down groundwater gradient edge of the landfill is not reliable for protecting offsite groundwaters from pollution by landfill leachate. For those landfills sited above fractured rock aquifers, the regulatory agency should be required to discuss in detail how leachate-polluted groundwaters that enter the fractured rock aquifer will be detected with a reliability of at least 95 percent.

Potential Change in Direction of Groundwater Flow. Another issue that needs to be considered in permitting landfills is the potential for a change in groundwater flow direction under and near the landfill. Because of the potential for adjacent and nearby properties to construct groundwater wells that could influence the local direction of groundwater flow in the vicinity of the proposed landfill, it will be essential that an ongoing groundwater flow direction evaluation be conducted to determine if new offsite production wells change the direction of groundwater flow and thereby lead to a requirement for additional monitoring wells in the new downgradient direction. That which is perceived to be down groundwater gradient at the time of landfill permitting will not necessarily be downgradient in the future. This type of monitoring program review will need to be conducted effectively forever, because of the very long period of time that the proposed Subtitle D landfill has the potential to pollute groundwaters with landfill leachate.

Evaluation of Leachate Density. According to Cherry (pers. comm., 1991), leachate from municipal landfills can contain sufficient amounts of salt to cause them to be somewhat more dense (heavier per unit volume) than the groundwaters of the area. This would cause a finger-plume of leachate to sink along its horizontal trajectory until it becomes sufficiently diluted so that its density matches that of the area groundwater. The hydrogeology and the groundwater characteristics of the area beneath and downgradient from a landfill must be defined with a high degree of certainty as part of permitting a landfill groundwater monitoring system, if a potentially meaningful groundwater monitoring program is to be developed to detect landfill leakage. Particular attention needs to be given to the depth of monitoring well screens that are designed to intercept the layer of leachate-polluted groundwater. The vertical position of the leachate plume that will occur at the point of compliance for groundwater monitoring should be predicted as part of permitting a landfill. Based on this prediction, the screening of monitoring wells to detect the maximum concentration of the leachate-polluted groundwaters at the point of compliance should be determined.

Some regulatory agencies allow monitoring wells that include well screening length over the depth of the aquifer. Substantial long-screened monitoring wells could withdraw from the aquifer large amounts of water that is not likely polluted by landfill leachate, thereby diluting the leachate-polluted water, which could lead to the inability to reliably detect a leachate plume that occurs in a narrow vertical band underlying the point of compliance for groundwater monitoring. A nested well sampling of various depths should be used, rather than a long-screen well.

State's Responsibility to Require Reliable Groundwater Monitoring. In a personal communication to G. F. Lee regarding the eventual leakage of single composite landfill liners and the unreliability of the groundwater monitoring systems being permitted by states, US EPA Headquarters Solid Waste staff (Geshwin) indicated that the inadequate groundwater monitoring systems being permitted are not the result of a deficiency in RCRA Subtitle D regulations. Rather, he indicated that it was the responsibility of the state regulatory agencies to ensure that the groundwater monitoring system permitted for a landfill will detect leachate-polluted groundwater when it first reaches the point of compliance for groundwater monitoring.

Responsibility for Long-Term Monitoring. Landfill proponents sometimes state that groundwater monitoring for the Detection Monitoring Program will be performed on a periodic basis during the active life of the landfill, as required by 40 CFR Part 258, Section 258.54(b). The active life of a landfill is the period during which wastes are received by it. The regulatory agency, as part of permitting a landfill, needs to specify who will be responsible for monitoring groundwaters during the 30-year postclosure period, which begins at the end of the active life of the landfill, and during the hundreds to a thousand or more years that the landfill will be a threat to generate leachate that will pollute groundwaters.

<u>Frequency of Groundwater Monitoring</u>. Landfill owners typically attempt to gain regulatory support for reducing the frequency of monitoring of groundwaters during the postclosure period. The approach that should be followed to enable reduced frequency of groundwater monitoring (such as from quarterly to semi-annually) should be based on an evaluation of the ability to predict with a high degree of reliability the composition of the groundwaters that will be found at the next monitoring event. If it is found that it is possible to reliably predict the

groundwater composition within a 95 percent confidence interval, then the frequency of monitoring can be reduced. However, if at any time in the future the predictability of the monitoring results no longer continues, then the frequency of monitoring should be increased. The same approach should be used to adjust the frequency of landfill gas monitoring and monitoring of the integrity of the landfill containment system.

Vertical Migration of Leachate-Polluted Groundwater in Wells

Einarson (2008) also discussed the concern about the potential for vertical transfer of water and associated pollutants within monitoring wells, as well as other wells, that are screened in two aquifers or that are not effectively sealed between the aquifers. There is need to consider the potential for transfer of water and pollutants between aquifers within a monitoring well at a landfill site. While it is often assumed by consultants to landfill applicants as well as by some regulatory agency staff that a low-permeability layer prevents the pollution of a lower aquifer, Einarson pointed out that there is often vertical transfer between stacked aquifers within monitoring wells. Fairly well-known, but frequently ignored, is the fact that the conventional approach for sealing wells with bentonite may not be effective in the short-term, or in the long-term, in hard-water systems because of cation exchange reactions between sodium bentonite and calcium ions that lead to shrinking and cracking of the seals. Those issues have been reviewed in by Lee and Jones-Lee (2006a), who also provide references to the work of others on the topic.

Unreliable Information on Detection of Landfill Liner Failure

A comment that is sometimes made by landfill proponents, their consultants, and some regulatory agency staff, in an attempt to support the reliability of single composite liners, is that there are no recorded instances where a single composite liner has been found to have failed. However, Lee and Jones-Lee (1999a) have discussed the inappropriateness of making this statement in support of the near-term, much less the long-term, ability of single composite liners to prevent groundwater pollution by landfill leachate for as long as the wastes in the landfill will be a threat. As Lee and Jones-Lee point out, in 1999 single composite liners had only been a national requirement for six years. With adequate quality assurance/quality control (QA/QC) in the construction of a single composite liner, leakage through that liner should not have occurred in 11 years. It should take longer than this to penetrate the clay component of the liner. Further, as discussed above, with inadequate QA/QC and/or inappropriate waste deposition which results in puncturing the plastic sheeting layer, and cracks developing in the clay layer underneath the areas of puncture, the plumes of leachate-polluted groundwater would either not yet have reached the point of compliance for groundwater monitoring or would not be detected at that point by the monitoring wells which are spaced too far apart relative to their zones of capture.

What is known (pers. comm., New York DEC staff) is that double composite lined landfills constructed in a number of areas (such as New York) have leaked leachate through the upper composite liner into the leak detection system between the two liners within a few years after construction. This is likely the result of inadequate QA/QC in upper composite liner construction and/or inappropriate waste placement in the landfill.

The failure to detect minimum Subtitle D landfill liner failures in the short period of time that such liners have been used is no indication of the long-term behavior of these liners in preventing groundwater pollution by landfill leachate for as long as the wastes in these landfills will be a threat.

Impact of Seismic Activity on Integrity of Landfill Containment Systems

Anderson (1995) published a summary review of the California Integrated Waste Management Board (CIWMB)'s evaluation of the impact of seismic activity on the integrity of MSW landfill containment systems based on the CIWMB staff's site inspections of about a dozen landfills following an earthquake. Anderson reported that the containment system of many of the landfills inspected showed damage that was attributed to the earthquake. He reported,

"Damage to landfills observed by the IWMB staff is categorized into four groups: 1. cracking of daily, intermediate, or final covers; 2. damage to liners; 3. damage to environmental collection and control systems; and 4. damage to infrastructure such as water tanks and on-site structures."

His review included a discussion of each of those categories. In addition to visual damage to the liners, there can be subsurface damage to the leachate collection system, liners, and other components that may not become apparent for many years. Such hidden damage is of particular concern at minimum design, single-composite-lined, Subtitle D landfills. As discussed herein, liner failure in a minimum design Subtitle D landfill will most likely first be detected in offsite production wells. This is expected because the typical groundwater monitoring wells arrays allowed by regulatory agencies consist of vertical monitoring wells spaced hundreds of feet apart at the point of compliance for groundwater. Such a system has a low probability of meeting the Subtitle D requirement to detect leachate-polluted groundwater when it first reaches the point of compliance. This issue is discussed elsewhere in this review.

Landfill Gas and Airborne Emission Problems

Municipal solid wastes and some industrial nonhazardous wastes contain organic compounds that are converted in a landfill by bacteria to methane and carbon dioxide (landfill gas). The presence of methane in landfill gas represents an explosive hazard and contributes to global warming. There have been explosions in dwellings on properties adjacent to landfills due to landfill gas subsurface migration to adjacent properties. In order to detect subsurface methane migration, landfill developers propose to ensure that the concentration of methane gas generated by the landfill does not exceed 25 percent of the lower explosive limit (LEL) for methane in landfill structures and that the concentration of methane gas does not exceed the LEL for methane at the landfill property boundary. While controlling landfill gas emissions to 25 percent of the lower explosive limit for methane, if adequately implemented, will eliminate the potential for explosions, it means that the landfill owner plans to have appreciable concentrations of landfill gas at adjacent property owners' property line. This approach is strongly contrary to the health, welfare and interests of adjacent property owners/users.

As landfill gas is generated within the landfill, it attempts to migrate in all directions, escaping through the bottom, sides and top surfaces. Some landfill developers install gas monitoring wells every 1,000 feet or so and test them quarterly for the presence of methane, using monitoring probes installed in the soil between the landfill unit and the property boundary or onsite structures (office, maintenance and scale). The spacing of landfill gas monitoring wells 1,000 feet apart is grossly inadequate to detect landfill gas migration through the subsurface soil under the conditions that will exist at many landfills. The escape of landfill gas from the proposed landfill will not be uniform across all areas of the landfill liner system that is used on the subsurface sides of the landfill. It will occur in areas where the liner has failed due to landfill construction problems, landfill operation problems and points of deterioration in the liner. This can lead to plumes of landfill gas that can pass between monitoring wells spaced 1,000 feet apart. As discussed by Hodgson et al. (1992), this, in turn, can be a threat to those who construct dwellings near the landfill property line.

The rate of landfill gas production is dependent on the moisture content of the wastes, where dry wastes produce little landfill gas. Landfill developers typically present estimates of the period of time that landfill gas will be generated in a proposed dry tomb landfill. As discussed by Lee and Jones-Lee (1999b), these estimates typically ignore the fact that, once the landfill is closed and the low permeability cover is installed, the rate of landfill gas generation will be greatly reduced or even stop as the wastes dry out, but landfill gas generation can begin to occur again when the low-permeability layer in the cover no longer keeps moisture out of the wastes.

Another issue that is not adequately addressed in the permitting of dry tomb Subtitle D landfills is that much of the waste placed in today's landfills is in plastic bags. Since these plastic bags are only crushed and not shredded, the crushed bags will "hide" the fermentable components of the waste that can lead to landfill gas formation. The net result is that, rather than landfill gas production following the classic generation rates and durations that were developed based on unbagged wastes or situations where much of the wastes in the landfill were able to interact with the moisture that enters the landfill during the first decade or so of landfill operation, the period of landfill gas production will be extended until the plastic bags decompose. This can readily be many decades, to a hundred or more years.

Prosser and Janechek (1995) have discussed that gaseous emissions from landfills are a threat to cause groundwater pollution that will not likely be detected by the groundwater monitoring wells, since gas migration can be in a direction different than down groundwater gradient. Richgels (2000) has provided additional information on landfill gas pollution of groundwaters based on his experience in investigating the situation near the Kiefer Landfill in Sacramento, California. The focus of his discussion is estimating reasonably foreseeable releases from municipal solid waste landfills. The California State Water Resources Control Board (SWRCB/CIWMB, 2006) landfilling regulations (Title 27) require that landfill owners make estimates of the potential for a particular landfill to release landfill gas and/or leachate to the environment. This information, in turn, is used to establish the magnitude of funding needed to remediate these releases should they occur at some time in the future.

Richgels (2000) has pointed out that landfill gas emissions, including the associated VOCs, from today's lined landfills are a much greater threat to cause widespread groundwater pollution than the expected initial near-term leakage of leachate through the HDPE compacted clay liner system. He recommends that landfill gas collection systems be developed that are designed and operated to more effectively control landfill gas emissions than is often done today. His recommendations include placing the leachate collection and removal system under vacuum to remove any landfill gas that collects in this system. This approach would tend to reduce the penetration of landfill gas through holes, rips, tears, etc., in the HDPE liner that can lead to groundwater pollution.

It is important to point out that the VOCs in landfill gas, such as the chlorinated solvents TCE, PCE and the transformation product vinyl chloride, which are often significant threats to cause groundwater pollution, can cause large-scale pollution of groundwaters by hazardous chemicals at concentrations above current drinking water MCLs – i.e., small amounts of landfill gas with its associated VOCs can pollute large amounts of groundwater. A recent National Academy of Sciences report (NAS, 2006) indicates that the current US EPA MCL for TCE may not be protective and therefore may need to be lowered.

While Richgels discussed the penetration of landfill gas through holes in the HDPE liner, in addition, as discussed above there can be permeation of these VOCs through intact liners (no holes). The thin film of leachate passing over the HDPE liner at the base of the leachate collection and removal system would contain landfill gas components that would permeate through the liner, leading to the potential for groundwater pollution by the VOCs.

Landfill gaseous emissions contain a variety of volatile hazardous chemicals that are a threat to cause cancer and other diseases in those living in or using areas near a landfill. While landfills contain landfill gas collection systems, such systems, even at the time of construction, are not fully effective in preventing landfill gas and other volatile waste components from escaping from the landfill through the landfill cover. Further, over time, the landfill gas collection system's reliability will deteriorate, or it may even become nonfunctional, leading to large-scale uncontrolled releases of landfill gas through the landfill cover and liner system.

Threat of Landfill Gas to Wildlife. Many reuse activities touted for land atop closed landfills are inappropriate and, indeed, pose a hazard because of landfill gas emission. It is known that even if a closed landfill incorporates a highly efficient landfill gas collection system, some landfill gas escapes through the cover. That gas contains hazardous and otherwise deleterious components including VOCs, many of which are carcinogens, and poses a threat to wildlife and other animals that may be in the area, such as those depicted in Waste Management ads grazing on the landfill cover vegetation and inhabiting the area. Landfill gas measurements are typically made several feet above the landfill surface where there has been some dilution of the gas with ambient air, rather than at the ground surface where many of the wildlife live or eat. The wildlife that lives or grazes at the land surface are thus exposed to higher concentrations of landfill gas and greater exposure to associated carcinogens than would be reflected by those measurements.

Landfill Odor Control Problems and Impacts. One of the components of landfill gas that is especially of concern to those living or working near a landfill is the malodorous compounds present in the gas. Municipal solid waste landfills are notorious for causing severe odor problems that can occur at considerable distances (sometimes miles) from the landfill. Landfill developers state at permitting hearings that the landfill operator will place daily and intermediate cover over the wastes, and additional control of odors will occur through limiting the size of the tipping face (where wastes are deposited each day). Some landfill developers will also state that if odor increases, additional cover material will be placed over the offensive material and/or a US

EPA-approved deodorizer will be installed to control the odor. When the landfill closes, the thick final landfill cover will further control the odors.

While typically landfill proponents will, as part of attempting to gain a permit, make such claims about controlling odors, frequently landfills with grossly inadequate buffer lands will cause odors on adjacent properties. While the trespass of landfill odors on adjacent properties is sometimes characterized as a "nuisance," in fact landfill odors represent significant health hazards. Shusterman (1992), a physician with the California Department of Health Services, has published a paper on the health threat that odorous conditions represent to those who experience obnoxious odors. Subsequently, Schiffman and Nagle (1992) and Schiffman et al. (1995, 2000, 2001a,b) have published several papers on the impacts of odors on human health, which demonstrate that obnoxious odors have significant heath impacts on some individuals. In addition to the health impacts of landfill odors, landfill gas releases that occur with the odors are known to contain carcinogens and other chemicals that, while not odorous, are a threat to human health. Landfill odors on adjacent properties are a good indicator that there are non-odorous compounds in the air that are a threat to health. With respect to using US EPA-approved deodorizers to "control the odor," such an approach is often not effective. Further and most importantly, while a deodorizer potentially can mask offsite odors, it does not control the hazardous chemicals that are present in the landfill gas emissions that reach offsite properties.

One of the major problems with controlling landfill odors is that regulatory agencies are often not effective in requiring that a landfill owner control odors so that they do not occur on adjacent properties. It is suggested that if a landfill is proposed to be permitted, a condition of the permit include the potential to permanently close the landfill and require the landfill owner to remove all wastes deposited in the landfill should landfill odors be detected at adjacent property owners' property lines more than once in a year. This approach would provide the landfill owner with the incentive to ensure that its so-called "odor control" approach is, in fact, effective in controlling odorous releases from the landfill.

Overall, landfill gas production in a dry tomb landfill is unreliably predicted over the period that the fermentable wastes will persist in a Subtitle D landfill. Further and most importantly, essentially no provisions are made to manage the landfill gas problems that will occur in dry tomb Subtitle D landfills over the time that the wastes in the landfill will be a threat to generate landfill gas.

Landfill Dust Control Problems. Dust emissions from landfills can be a severe problem that can impact adjacent properties. There are several aspects of the dust control issue that need to be evaluated. First, the landfill owner should be required to control all dust emissions from the landfill so that no dust from the landfill is deposited on adjacent properties. Some landfill operators use landfill leachate for dust control. While in the past this was a common practice, in many states it is no longer allowed, since it can lead to polluted stormwater runoff. Leachate should not be used for dust control, since leachate contains a variety of hazardous and deleterious chemicals that can be present in stormwater runoff from the areas to which the leachate is applied.

Some landfill owners/operators' proposed potential use of a "dust palliative" can lead to significant public health and environmental problems. The senior author of this report was a member of a US EPA expert panel on evaluating the potential public health and environmental impacts of various types of chemicals that are used for dust control. As part of this effort, Lee and Jones-Lee (2004c) developed a report discussing the potential public health and environmental problems associated with the chemicals, including wastes that are used as dust suppressants. It is this type of practice that led to the Times Beach, Missouri, dioxin situation, where waste products (stillbottoms) from a chemical manufacturing operation were used as dust suppressants on roads. Similar situations have occurred where transformer oils containing PCBs have been used as dust suppressants on roads. At this time, dust suppressants are largely unregulated with respect to environmental pollution. All dust suppressants used at a landfill should be evaluated in accordance with the procedures discussed by Lee and Jones-Lee (2004c).

Stormwater Runoff Pollution Control

Stormwater runoff from landfills can have a significant adverse impact on the water quality of the receiving waters for the runoff with respect to their use for domestic water supplies and their ability to support aquatic life. Stormwater runoff from landfill properties can contain a variety of regulated and many unregulated pollutants that are a threat to the health of those who use the treated waters for domestic purposes. Also, while not necessarily a human health threat, MSW contains a large number of chemicals that can be highly detrimental to the use of MSW leachate-polluted waters for domestic purposes. Of particular concern are those chemicals that can cause tastes and odors. Current water quality regulatory programs only regulate 100 to 200 of the many thousands of chemicals present in municipal and industrial solid wastes that can be legally added to the waste stream that is deposited in MSW landfills. As discussed below, the monitored/regulated chemicals in landfill leachate and stormwater runoff represent a very small part of the chemicals present in municipal solid wastes that are a threat to public health and the environment.

During the active life of a landfill (when wastes are being deposited in the landfill), waste-derived constituents can escape from the landfill active face through windblown transport; via bird, insect and vermin transport; and by stormwater runoff from the active face. While typical state and local landfilling regulations require that the active face of the landfill be kept to a "small" area, there is still escape of waste-derived constituents which can be transported by stormwater to offsite watercourses.

A source of pollutants for stormwater runoff from landfill property is leachate spills on the ground surface. These spills are associated with inadequate handling of leachate from the leachate collection system discharge point to the location where it is transported offsite, or at the onsite treatment works. Also of concern is the breakage of leachate transmission pipes that results in the discharge of leachate to the ground surface. These types of problems are especially prevalent in climates where freezing of the leachate pipes can occur.

An issue of particular concern in closed landfills is the development of leachate seeps that pollute stormwater runoff from the landfill. Seeps are of concern, since often stormwater runoff from landfills is polluted by landfill wastes, chemicals and pathogens. Often large parts of a landfill will be above the existing ground surface, where there is the potential for seeps of

leachate to occur through the sides of the aboveground parts of the landfill, which could pollute stormwater runoff from the landfill surface. These seeps can occur at any time over the thousands of years that the wastes in the landfill will be a threat. There will be need to control stormwater pollution from the landfill, effectively forever.
At one time the use of landfill leachate for dust control was widely practiced. Since this approach can lead to highly polluted stormwater runoff it should not be allowed. Also of concern is the use of other types of wastes for dust control. These wastes/chemicals can cause stormwater runoff to pollute waters receiving the runoff. While the pollutants in leachate used for dust control or from seeps would accumulate in the landfill stormwater detention basins for storms of magnitude less than the 25-year, 24-hour discharge, storms of greater than this magnitude could tend to flush out the pollutants in the detention basins onto downstream properties. Further, there will be need for *ad infinitum* maintenance of the detention basins to ensure that as they accumulate sediments they do not lose their capacity to control runoff from the landfill area for storms less than the 25-year, 24-hour event.

Under the current US EPA regulations with no assured funding beyond 30 years after closure of the landfill, there are significant questions about whether the limited stormwater runoff monitoring and maintenance of detention basins that are designed to only contain the 25-year, 24-hour storm will be contained/maintained for as long as the wastes in the landfill are a threat to generate leachate, which for dry tomb type landfills can be forever. The 25-year, 24-hour storm limitation in the design of the detention basins means that larger storms will discharge pollutants to nearby watercourses without even removal of the large size erosion particles and wastes. If two storms occur, one shortly after the other, where the detention basins still have appreciable water from the first storm, means that the second storm's runoff will likely pass through the detention basins even if neither storm exceeds the design capacity of a 25-year, 24-hour storm.

There are other sources of pollutants in landfill stormwater runoff. Garbage truck traffic, landfill equipment such as bulldozers, compactors etc, spills of fuels and engine oil where the old oil is allowed to be dumped on the ground etc can be sources of pollutants for runoff from landfills.

Current federal and many state stormwater runoff regulations governing landfills do not require that the stormwater runoff from a landfill area be treated to reduce the waste-derived chemicals to meet water quality criteria and drinking water maximum contaminant levels (MCLs). The only treatment typically provided is a settling basin that will detain low volumes of stormwater runoff.

For those landfills with a single composite liner, the leachate pollution of shallow groundwater can be a source of surface water pollution if the polluted shallow groundwater enters the surface waters through above-water surface springs or below-water surface discharges to streams, rivers, lakes and nearshore/offshore marine/estuarine waters.

The use of pesticides/herbicides to control insects/weeds at the landfill can be a source of pollutants in stormwater runoff that can be adverse to drinking water quality and a threat to aquatic life in the receiving waters for the runoff.

The area where waste is dumped for load inspection can be a source of stormwater runoff pollutants if the wash-down water is not adequately controlled. A similar situation can exist in areas where mud on truck tires is washed off to keep from transporting landfill-area-derived mud to the public roads.

In addition to deficiencies in chemical monitoring, many regulatory agencies do not require aquatic life toxicity monitoring. Such monitoring should include the standard three species toxicity testing required by the US EPA, which is conducted on domestic and industrial wastewater effluents.

The nature of stormwater runoff impacts is that of pulses of pollutants that can be disruptive to a water supply's ability to adequately treat the stormwater runoff-polluted water to maintain high water quality in the treated waters. At this time the information on the water quality impacts of stormwater runoff from landfill areas is not sufficiently known to be able to qualitatively predict the potential impacts of landfill stormwater runoff on receiving water quality. However, it is well known that municipal solid waste landfills contains large amounts of chemicals that have the potential to adversely impact domestic water supply water quality and the aquatic life resources of waterbodies.

The regulation of landfill stormwater runoff water quality impacts occurs under the US EPA National Stormwater Runoff permit system. Nationally and in states, stormwater runoff from a landfill is regulated as an "industrial" source. Critical review of the existing landfill stormwater runoff monitoring requirements shows that they are seriously deficient in providing the monitoring needed to insure with a reasonable degree of certainty that the landfill stormwater runoff will not pollute the waters receiving the runoff from the landfill. MSW and its leachate contain thousands of chemicals that are not monitored/regulated, which are a threat to public health and the environment. Some of the unmonitored constituents can be adverse to public health at very low concentrations. Dr. Christian Daughton (2005), Chief of the Environmental Chemistry Branch, National Exposure Research Laboratory, Office of Research and Development, US EPA, Las Vegas, Nevada, has discussed the inadequacy of water quality monitoring programs in identifying pollutants in wastewaters/stormwater runoff for the range of chemicals that could be impacting public health and the environment. In his presentation he stated,

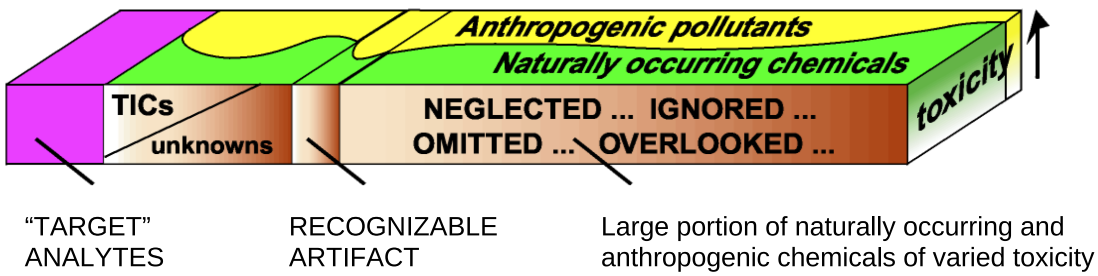
"Further Truisms Regarding Environmental Monitoring

- *What one finds usually depends on what one aims to search for.*
- *Only those compounds targeted for monitoring have the potential for being identified and quantified.*
- *Those compounds not targeted will elude detection.*
- *The spectrum of pollutants identified in a sample represent but a portion of those present and are of unknown overall risk significance."*

Figure 7 presents a diagram of this situation. This figure is from web page: "The Critical Role of Analytical Chemistry," C.G. Daughton, July 2002.
http://www.epa.gov/nerlesd1/chemistry/pharma/critical.htm

Background information on unrecognized/unregulated chemicals as environmental pollutants is available at http://www.epa.gov/nerlesd1/chemistry/pharma/ and at http://www.epa.gov/nerlesd1/chemistry/ecb-posters.htm.

Figure 7
Chemical Analysis Output for a Typical Environmental Sample



TICs = tentatively identified compounds, from: C.G. Daughton, US EPA (July 2002)

In addition, Lee and Jones-Lee (2005b) have recently published a review on unrecognized pollutants.

Safe Drinking Water Act Source Protection Issues

The federal Safe Drinking Water Act as amended in 1996 established the requirements that each state must develop a source water quality protection program that identifies the potential sources of pollutants in a domestic water supply watershed that are a threat to the water supply water quality. It should be understood that the US EPA Subtitle D regulations and state regulations governing developing MSW landfills do not adequately consider the protection of domestic water supply water from landfill area stormwater runoff-derived pollutants. The US EPA national stormwater runoff water quality regulations also do not adequately and reliability establish stormwater runoff water quality management programs to protect domestic water supplies from landfill waste-derived pollutants.

The Safe Drinking Water Act regulates the degree of treatment that is needed to produce an acceptable treated water. This Act, while helping state regulatory agencies and water utilities assess potential pollutant sources that could adversely impact domestic water supply water quality, has no regulatory authority to restrict land use in a water supply watershed. Since neither the US EPA Subtitle D landfill regulations nor the US EPA stormwater runoff water quality regulations can be used to adequately protect domestic water supply water quality, the burden of watershed water supply water quality will fall to the water utility and those concerned with protecting water quality in a domestic water supply. Water utilities should work with the watershed area planning agency to restrict the development of new sources of pollutants that are a significant threat to the water supply water quality. The development of new landfills in a small domestic water supply watershed is a situation where water utilities should work with local zoning agencies to restrict the development new landfills in their watershed. This is prudent public health and aquatic life water quality protection policy.

The agencies responsible for the domestic water source water quality assessment should identify MSW landfills as a potential long-term source of a wide variety of pollutants that must be carefully monitored during the active life of the landfill and the postclosure period; i.e., while the wastes are still a threat to generate leachate when contacted with water. As an example of this situation, Meriwether County, Georgia, adopted a zoning ordinance that prohibits the siting of MSW landfills in small domestic water supply watersheds, which is in accord with protection of the water quality impacts of landfill releases of waste-derived constituents. Lee (2005) and Lee and Jones-Lee (2008) has reviewed this situation, where he points out that this approach is appropriate as part of domestic water supply source water quality protection from pollution from landfills.

Inadequate Postclosure Monitoring and Maintenance

The 30-year funding period for postclosure monitoring and maintenance of Resource Conservation and Recovery Act Subtitle C and D landfills that was specified by Congress was one of the most significant errors made in developing RCRA Subtitle C and D landfilling regulations. Those who were responsible for developing this approach did not have an understanding of how waste-associated constituents would degrade/transform in a dry tomb landfill. The US Congress General Accounting (now Accountability) Office (GAO, 1990), in the Executive Summary of its report "Funding of Postclosure Liabilities Remains Uncertain," under a section labeled "Funding Mechanisms Questionable," concluded that,

> *"Owners/operators are liable for any postclosure costs that may occur. However, few funding assurances exist for postclosure liabilities. EPA only requires funding assurances for maintenance and monitoring costs for 30 years after closure and corrective action costs once a problem is identified. No financial assurances exist for potential but unknown corrective actions, off-site damages, or other liabilities that may occur after the established postclosure period."*

Further, the US EPA Inspector General (US EPA, 2001b) in a report, "RCRA Financial Assurance for Closure and Post-Closure," developed similar conclusions:

> *"There is insufficient assurance that funds will be available in all cases to cover the full period of landfill post-closure monitoring and maintenance. Regulations require postclosure activities and financial assurance for 30 years after landfill closure, and a state agency may require additional years of care if needed. We were told by several state officials that many landfills may need more than 30 years of post-closure care. However, most of the state agencies in our sample had not developed a policy and process to determine whether post-closure care should be extended beyond 30 years, and there is no EPA guidance on determining the appropriate length of post-closure care. Some facilities have submitted cost estimates that were too low, and state officials have expressed concerns that the cost estimates are difficult to review."*

As indicated by Skinner, current Executive Director of SWANA (quoted above),

> *"The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and someone needs to be responsible for stepping in and taking corrective action when a problem is detected. The federal Subtitle D rules require only 30 years of post-closure monitoring by the landfill operator, however, and do not require the operator to set aside funds for future corrective action. Given the many difficulties of ensuring and funding perpetual care by the landfill operator, the responsibility of responding to long-term problems at dry-tomb landfills will fall on future generations, and the funding requirements could quite likely fall on state and local governments."*

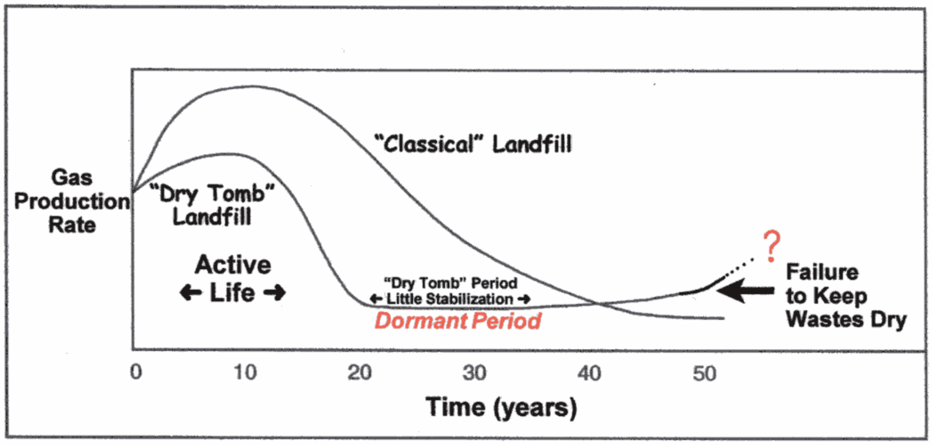
Typically those developing a landfill propose to only be responsible for providing the financial assurance for: closure; postclosure and corrective action for the 30-year minimum period. Hickman (1992, 1995, 1997) and Hickman and Lanier (1998), in a series of articles ("Financial Assurance-Will the Check Bounce?", "Ticking Time Bombs?", "No Guarantee," "A Broken Promise Reversing 35 Years of Progress"), has discussed the inadequate approaches for postclosure funding under Subtitle D regulations. Lee and Jones-Lee (1992, 1993b, 2004d) and Lee (2003c) have published a number of reviews on the need for longer-term postclosure care, as well as the use of more reliable financial instruments to provide funding during the postclosure care period than is typically provided today.

Lee and Jones-Lee (2004d) have discussed the unreliable information that some private landfill owners and their consultants are foisting on regulatory agencies where they claim that it is possible to predict, based on landfill monitoring, the duration of postclosure care. This is an attempt to try to limit the long-term liability of landfill owners for postclosure care. As discussed by Lee and Jones-Lee (2004d), such claims ignore the processes that will take place in a dry tomb type landfill. Figure 8 provides a diagram of the expected situation with respect to landfill gas formation and leachate generation in a closed dry tomb landfill. A similar relationship has been developed by the California Integrated Waste Management Board (CIWMB, 2004). Once the landfill is closed with a low-permeability cover, the rate of landfill gas generation and leachate production will drop off and eventually stop if the landfill cover is effective in limiting moisture from entering the landfill. This is because both leachate generation and landfill gas production are dependent on moisture in the wastes.

Christensen and Kjeldsen, (1989) have discussed the role of moisture in influencing landfill gas production. These relationships are shown in Figure 9. However, in time, as the low-permeability plastic sheeting layer in the cover deteriorates and moisture enters the landfill, landfill gas and leachate generation will start to occur again. There is no reliable way, under current dry tomb Subtitle D landfill cover design and monitoring, to predict when the postclosure dormant period will end and landfill gas and leachate production will begin to occur again.

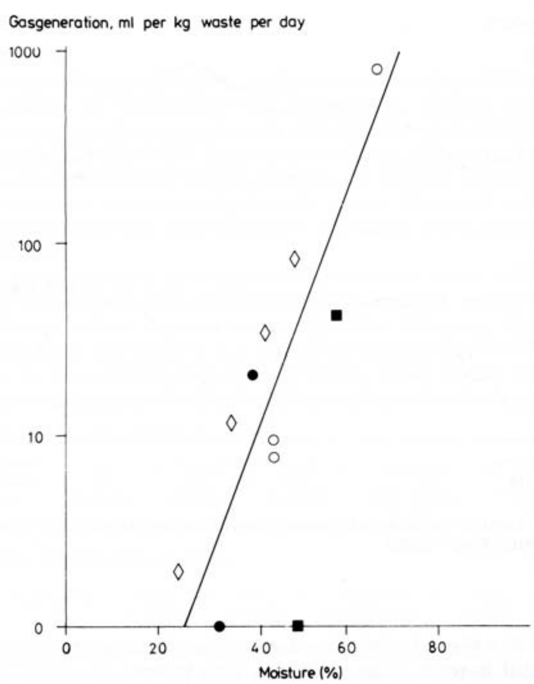
The CIWMB, in accord with California Title 27 landfilling regulations of requiring postclosure monitoring and maintenance for as long as the wastes in the landfill will be a threat, is in the process of developing an approach to secure assured funding for postclosure monitoring and maintenance of closed landfills. Landfill owners, especially private owners, have voiced opposition to this approach. Lee and Jones-Lee (2007b) have provided the CIWMB with comments in support of its current efforts.

Figure 8. Comparison of Pattern of Landfill Gas Generation over Time at Classical Sanitary Landfill and "Dry Tomb" Landfill



(from Lee and Jones, 1991)

Figure 9. Impact of Moisture on Landfill Gas Formation
(from Christensen and Kjeldsen, 1989)



Regulatory Agency Should Define Who Will Provide Postclosure Care for as Long as the Wastes Will Be a Threat. As part of permitting a landfill, the regulatory agency should provide information on who will provide the following for as long as the wastes in the landfill will be a threat:

- Monitoring the groundwater monitoring wells and the gas monitoring wells,
- Removing leachate from the leachate collection sumps,
- Repairing the cover when there is erosion of it and it fails to prevent moisture from entering the landfill that generates leachate,
- Cleaning out the leachate collection system associated with chemical and biological plugging of this system,
- Operating and maintaining the landfill gas collection system,
- Performing groundwater remediation when the pollution of groundwater by landfill leachate is discovered in a monitoring well or more likely in an offsite production well,
- Replacing the domestic water supply sources for nearby property owners/users when the groundwaters that they are using for domestic water supply are polluted by landfill leachate, and
- Funding the liability for lawsuits that will result from developing and permitting a landfill that will obviously pollute groundwater during the time that the wastes in the landfill will be a threat.

Since the wastes in a dry tomb landfill will be a threat to generate leachate and landfill gas for well beyond the 30 years of minimum postclosure monitoring and maintenance that the landfill proponent will be obligated to cover, regulatory agency staff should estimate the period of time that postclosure funding will be needed (including the technical basis for developing this estimate), how much funding will be needed to address all plausible worst-case failure scenarios for the landfill cover, bottom liner, and groundwater and gas monitoring systems, and the source of the funds for the required postclosure monitoring, maintenance and remediation.

From an overall perspective, minimum Subtitle D landfill design, closure and postclosure monitoring and maintenance will result in the development of a landfill that will pollute groundwater by landfill leachate during the period of time that the wastes in the landfill will be a threat. This pollution will be a significant threat to the health, welfare and interests of the residents and property owners in the area.

Hazardous versus Nonhazardous Waste Classification

The typical approach that is used by regulatory agencies and landfill proponents is to say that no "hazardous wastes" will be deposited in a Subtitle D landfill. However, that statement is based on the fact that an arbitrary and often not protective approach is used to define "hazardous" waste. An understanding of the basis of this classification shows that the US EPA's approach allows substantial amounts of hazardous chemicals to be added to so-called "nonhazardous" waste (Subtitle D) landfills. Further, the US EPA's classification system provides for no recognition of so-called "nonhazardous" waste containing constituents which are highly detrimental to the use of the groundwaters that are polluted by leachate from such wastes, rendering the waters unusable for domestic and many other purposes. As discussed by Jones-Lee and Lee (1993), the presence in a water supply well of municipal solid waste and other waste leachate, with no "hazardous" chemicals above the US EPA criteria that are used to make the distinction between hazardous and nonhazardous, can still cause the water supply well to have to be abandoned because of the aesthetic problems of taste and odor, color, iron, manganese, hydrogen sulfide, corrosion, scaling, etc.

The most significant problem with the US EPA's classification of hazardous versus nonhazardous waste is the use of the leaching test – originally, the EP-Tox test, and now the toxicity characteristic leaching procedure (TCLP). The test is patterned after dredged sediment elutriation. While the dredged sediment elutriation conditions make sense for dredged sediment open-water disposal, similar conditions have no validity for the leaching of constituents in a solid waste landfill. The liquid-to-solid ratios used, redox conditions, pH and exposure surface area of the solid particles are all highly arbitrary. The EP-Tox test, now TCLP, is a political test designed to limit the size of the hazardous waste stream that must be managed as hazardous waste. The tests have little or nothing to do with properly evaluating chemicals that could affect groundwater quality.

The interpretation of what constitutes excessive leaching in the EP-Tox test and TCLP is another example of an arbitrary approach on the part of the US EPA in defining hazardous waste. The allowed attenuation factor (5-to-1 dilution is assumed) will, for some hydrogeological groundwater systems, be overprotective, and for others, under-protective. Yet the characteristics of the hydrogeology of the site are not taken into account in interpreting the results of the test to determine whether a waste can be placed in a nonhazardous waste landfill.

There is considerable unreliable information on the potential for municipal solid waste leachate to pollute groundwaters, rendering them unusable for domestic and many other purposes. Jones-Lee and Lee (1993) have presented a review of the potential for MSW leachate to pollute groundwaters. As they discuss, MSW leachate typically contains high concentrations of conventional and so-called "non-conventional" pollutants. The conventional pollutants include heavy metals, a variety of organics, and various salts, some of which are hazardous to the health of those who consume water that has been polluted by municipal landfill leachate.

Non-conventional contaminants are largely organic chemicals that have not been defined, and whose potential hazards to public health and groundwater quality are not known. Typically the organic Priority Pollutants – those organics that are identified and quantified – represent a very small fraction of the total organic matter present in leachate as measured by chemical oxygen demand and total organic carbon. It is estimated that from 90 to 95 percent of the organic materials in municipal landfill leachate are of unknown composition. Those chemicals have not been identified, and obviously their potential impacts on public health and groundwater quality are unknown.

Inadequate Waste Screening for Prohibited Wastes. Landfill operators are required to have a prohibited waste control program on site to detect and deter attempts to dispose of unacceptable wastes at the landfill (such as hazardous wastes that are not conditionally exempt small quantity generator wastes). Frequently, inadequate information is provided on the program that the landfill developer plans to implement that would prevent unacceptable wastes from being deposited in the landfill. The approach of having the scale personnel examine from three to five random loads on a random day once per week is far from adequate in evaluating whether the municipal solid waste stream deposited at the landfill contains wastes that cannot be legally deposited in the landfill.

Hazardous Characteristics of MSW. While municipal landfills are not allowed to accept "hazardous waste," they can and do accept a wide variety of hazardous chemicals or materials which contain hazardous chemicals. Common household items such as batteries, fluorescent bulbs and cleaning fluids contain such hazardous chemicals. One of the groups of chemicals of particular concern is the heavy metals, such as lead, cadmium, etc., which are known to be highly toxic to people. SWANA (2004) issued a report which claims that the concentrations of heavy metals in today's municipal landfill leachate are not a threat to cause groundwater pollution. However, as discussed by Lee (2004), the SWANA analysis of the situation is flawed in that they used a regulatory approach adopted by the US EPA to define the critical concentrations of heavy metals in landfill leachate that are a threat to domestic water supplies. As discussed by Lee (2004, 2006e), these critical concentrations are at least 100 times the drinking water maximum contaminant levels (MCLs). Further, the US EPA's approach for waste classification as hazardous versus nonhazardous ignores the fact that there are geological strata (such as fractured rock) where there can be rapid, little-attenuated heavy metal movement through groundwater systems to domestic water supply wells.

The facts are that the heavy metals in MSW leachate today are a threat to cause groundwater pollution which is adverse to public health and domestic water supply water quality. The US EPA (1988a), in reviewing this situation, concluded that the contamination of a groundwater by MSW leachate renders the groundwater and the area of contamination of the aquifer unusable for domestic purposes, where a water supply well that intercepts leachate-polluted groundwater has to be abandoned – i.e., cannot be cleaned up to acceptable public health standards.

Those familiar with groundwater monitoring near landfills understand that today's chemical-based approach – where a few regulated chemicals are monitored, compared to the thousands to tens of thousands of chemicals that are present in the wastes that are a threat to public health, groundwater resources and the environment – is significantly deficient and is not protective of public health or the environment. Lee and Jones-Lee (1994c), in a paper, "Does Meeting Cleanup Standards Mean Protection of Public Health and the Environment?" have discussed this issue, pointing out that waters that have been contaminated by wastes that meet all MCLs can still be a significant threat to public health, through the hazards of unregulated chemicals for which there are no MCLs.

The US Congress General Accounting Office (GAO) has indicated that there are in excess of 75,000 chemicals used in US commerce today. The current US EPA and state regulatory agency "laundry list" of chemicals that are analyzed associated with a solid waste landfill represents 100 to possibly 200 of these chemicals. There are thousands to tens of thousands of chemicals present in municipal solid waste and industrial so-called "nonhazardous" waste of the type that could be disposed of in a municipal solid waste landfill, that need to be, but that are not now required to be monitored, either directly or by their impacts, through biological assessment techniques, in order to protect public health and the environment.

As an example of the lack of adequate monitoring of the characteristics of municipal landfill leachate, Gintautas et al. (1992) reported finding a phenoxyalkanoic acid herbicide in municipal landfill leachate which had not been previously reported. They concluded that the chlorinate 2-phenoxypropionic herbicides are ubiquitous in MSW landfill leachates in the US. These herbicides are used on residential lawns for control of broadleaf plants (dandelions). Since grass clippings are allowed in the municipal solid waste stream, chemicals used on the lawn would be present in grass clippings that are deposited in the landfill. However, neither the US EPA nor the state regulatory agencies are requiring the analysis of leachate for the wide variety of chemicals that are used on residential properties and in the home that become part of the municipal solid waste stream.

Recently, Dr. C. Daughton (2004a,b), Chief, Environmental Chemistry Branch, US EPA National Exposure Research Laboratory, made a presentation, "Ubiquitous Pollution from Health and Cosmetic Care: Significance, Concern, Solutions, Stewardship – Pollution from Personal Actions." This presentation covered information on pharmaceuticals and personal care products (PPCPs) as environmental pollutants. He also discussed the relationship between endocrine disrupters and PPCPs. (A copy of Daughton's presentation, which consisted of 64 PowerPoint slides, is available upon request from gfredlee@aol.com.)

Daughton pointed out that there is a wide variety of chemicals that are introduced into domestic wastewaters and wastes that are being found in the environment. These include various chemicals (pharmaceuticals) that are derived from usage by individuals and for pets, disposal of outdated medications in sewerage systems and solid waste streams, release of treated and untreated hospital wastes to domestic sewerage systems, transfer of sewage solids ("biosolids") to land, industrial waste streams, releases from aquaculture of medicated feeds, etc. Many of these chemicals are not new chemicals. They have been in wastewaters and municipal solid wastes for some time, but are only now beginning to be recognized as potentially significant water pollutants. They are largely unregulated as water pollutants.

According to Daughton (2004a),

> *"Since the 1970s, the impact of chemical pollution has focused almost exclusively on conventional "priority pollutants," especially on those collectively referred to as "persistent, bioaccumulative, toxic" (PBT) pollutants, "persistent organic pollutants" (POPs), or "bioaccumulative chemicals of concern (BCCs). The "dirty dozen" is a ubiquitous, notorious subset of these, comprising highly halogenated organics (e.g., DDT, PCBs). The conventional priority pollutants, however, are only one piece of the larger risk puzzle."*

Daughton has indicated that there are over 22 million organic and inorganic substances, with nearly 6 million commercially available. The current water quality regulatory approach addresses less than 200 of these chemicals, where in general PPCPs and many other chemicals are not regulated. According to Daughton, "*Regulated pollutants compose but a very small piece of the universe of chemical stressors to which organisms can be exposed on a continual basis.*" Daughton has indicated that one of the routes of environmental exposure is through trash placed in municipal solid waste landfills. He specifically singles out "leaching from municipal landfills" as an origin of PPCPs in the environment. He characterizes municipal landfills as "*pollution postponement*." MSW landfills receive substantial amounts of pharmaceuticals and other unregulated/unmonitored chemicals that become present in landfill leachate. In addition to being present in surface waters and groundwaters polluted by landfill leachate near the landfill, the disposal of MSW leachate in POTWs (municipal wastewater treatment plants) contributes to the pollution of the environment through discharges of "treated" wastewaters to surface waters. Additional information on PPCPs is available at www.epa.gov/nerlesd1/chemistry/pharma/index.htm.

Periodically, previously unrecognized significant environmental pollutants are being found in surface waters or groundwaters. Two recent examples of this situation are perchlorate and the polybrominated diphenyl ethers (PBDEs). With respect to perchlorate as a widespread water pollutant, Silva (2003) of the Santa Clara Valley Water District in California, has discussed the potential for highway safety flares to be a significant source of perchlorate (ClO_4^-) contamination to water, even when the flares are 100-percent burned. According to Silva,

> *"A single unburned 20-minute flare can potentially contaminate up to 2.2 acre-feet* [726,000 gallons] *of drinking water to just above the California Department of Health Services' current Action Level of 4 µg/L* [for perchlorate]*."*

Silva points out that, *"More than 40 metric tons of flares were used/burned in 2002 alone in Santa Clara County."* Silva also indicates that fully burned flares can leach up to almost 2,000 µg of perchlorate per flare. The spent/used highway flares are often disposed of as trash in municipal landfills. This can be a source of perchlorate in MSW leachate. California's Office of Environmental Health Hazard Assessment (OEHHA, 2004) has recently proposed a public health goal for perchlorate of 6 µg/L. As of December 2003, there were 354 public wells in California with perchlorate above the proposed limit of 6 µg/L.

Another widespread "new" pollutant has been recently discussed by Hooper (2003) of the Hazardous Materials Laboratory, Department of Toxic Substances Control, California EPA. He states,

> *"Over the past 25 years, tens of thousands of new chemicals (7 chemicals per day) are introduced into commerce after evaluation by USEPA. Few (100-200) of the 85,000 chemicals presently in commerce are regulated. We have reasons to believe that a much larger number than 200 adversely affect human health and the environment."*

As an example of unidentified hazardous chemicals in the environment, Hooper discussed finding PBDE (polybrominated diphenyl ether) in human breast milk and in San Francisco Bay seals. Archived human breast milk shows that this is a problem that has been occurring for over 20 years. According to McDonald (2003) of California Environmental Protection Agency, Office of Environmental Health Hazard Assessment,

> *"Approximately 75 million pounds of PBDEs are used each year in the U.S. as flame retardant additives for plastics in computers, televisions, appliances, building materials and vehicle parts; and foams for furniture. PBDEs migrate out of these products and*

into the environment, where they bioaccumulate. PBDEs are now ubiquitous in the environment and have been measured in indoor and outdoor air, house dust, food, streams and lakes, terrestrial and aquatic biota, and human tissues. Concentrations of PBDE measured in fish, marine mammals and people from the San Francisco Bay region are among the highest in the world, and these levels appear to be increasing with each passing year."

The California Office of Environmental Health Hazard Assessment (OEHHA 2006) has published a review on the potential for PBDEs to be environmental pollutants and the health hazards associated with them. Renner (2000) published a review on PBDEs, which provides additional information on their sources, occurrence and potential significance as environmental pollutants.

PBDEs are similar to PCBs and are considered carcinogens. Some of the PBDEs are being banned in the US and in other countries. PBDEs are present in the municipal solid waste stream.

The perchlorate and PBDE situations are not atypical of what could be expected based on the approach that is normally used to define constituents of concern in water pollution control programs. Based on the vast arena of chemicals that are used in commerce, many of which could be present in aquatic systems through wastewater discharges and so-called nonhazardous solid wastes, it is likely that many other chemicals will be discovered in the future that are a threat to aquatic ecosystems and public health through surface water and groundwater pollution.

In summary, MSW leachate contains a vast array of unrecognized hazardous chemicals that are a threat to public health and the environment through pollution of domestic water supplies. Lee and Jones-Lee (2005b) have recently published a review on unrecognized pollutants.

While often not considered and largely unregulated, municipal solid waste leachate contains a variety of human and animal fecal waste and other wastes that contain disease organisms, such as bacteria, viruses, cyst-forming protozoans and intestinal parasitic worms. Of particular concern are sewage sludge and diapers. As discussed below, vermin (small animals, including insects) and birds can transport disease organisms from the solid wastes to the areas near the landfill, thereby exposing people and animals to disease organisms.

Construction and Demolition Waste Landfilling

Associated with the construction of new structures are various types of waste materials that are landfilled. Redevelopment of areas often requires demolition of existing structures that also need to be landfilled. This leads to construction and demolition (C&D) wastes as a special category of solid waste materials that are landfilled. There are no federal regulations governing the landfilling of C&D wastes. Each state has developed its own regulatory approach. These approaches range from deposition of C&D wastes in MSW landfills, to landfilling with limited environmental protection with respect to liners for leachate collection, groundwater monitoring, etc. There is a basic problem with the regulation of the landfilling of C&D wastes, in that some regulatory agencies consider C&D wastes to be "inert," and therefore a limited threat to cause environmental pollution. However, as discussed below, there is substantial evidence that C&D wastes generate leachate that represents a significant threat to cause groundwater pollution.

ICF Inc. (1995a), under contract with the US EPA Office of Solid Waste, conducted a review of the characteristics of leachate generated by construction and demolition waste landfills. Construction and demolition landfill leachate sampling data were collected from 21 C&D landfills. Data were provided for 305 parameters. Potentially significant concentrations, compared to drinking water maximum contaminant levels (MCLs), were found of 1,2-dichloroethane, methylene chloride, cadmium, iron, lead, manganese and total dissolved solids (TDS).

ICF Inc. (1995b) conducted a review of the "damage cases" caused by construction and demolition waste landfills. ICF Inc. (1995b) identified 11 damage cases where there was groundwater contamination by the C&D landfill. Constituents causing groundwaters to exceed the drinking water MCL were iron, manganese, TDS and lead. According to ICF Inc. (1995a), there were over 1,800 C&D landfills operating in the United States in the mid-1990s. Therefore, only a small number of the C&D landfills have been examined for groundwater pollution.

The Ohio Environmental Protection Agency recently characterized C&D landfill leachate production from several sites. This report found that leachate from construction and demolition landfills contains a number of contaminants at levels that are a potential threat to environmental quality. The results of these analyses are available through the Ohio Environmental Council website, http://www.theoec.org/hottopics_pressroom.html. In the section labeled "Arsenic, Lead & Pesticides Found in C&DD Landfills" are links to the Ohio EPA report on C&DD (construction and demolition debris) landfill leachate, as well as a number of other sources of information on C&DD landfills.

In addition to the recognized pollutants in household items, there is increasing recognition that homes contain a wide variety of chemicals that when placed in a landfill will cause environmental pollution. As discussed above, Daughton (2002; 2004a,b) has reviewed the fact that the current water quality monitoring programs for characterizing landfill leachate in groundwaters polluted by landfills are significantly deficient in describing the full range of pollutants that are a threat to public health and the environment.

Recently, it has become more widely recognized that construction and demolition wastes can contain appreciable concentrations of PCBs. For many years PCBs were used in sealants in concrete joints and wooden structures. This means that construction and demolition wastes can contain PCBs. This issue has been recognized in Europe, Australia and other countries. There are a number of papers and reports on this issue from other countries, which provide additional information on the presence of PCBs in various types of structures. Of particular concern are the publications by Åstebro et al. (2000), BUWAL (date unknown) and CFMEU (date unknown). A comprehensive review of what was known in 2004 about PCBs in structures as a diffuse source of PCBs for the environment has been developed by Kohler et al. (2005).

The authors of this report have been involved in the review of several C&D landfilling situations. These include evaluating the potential threat of expanding the Taylorsville Road Hardfill Landfill in Huber Heights, Ohio (Lee 2002). It was concluded that the expansion of this landfill was a threat to the domestic groundwater supply water quality for Huber Heights. More recently, the authors have been involved in the review of two proposed C&DD landfills in Morrow County, Ohio (Lee 2006f), and in evaluating the potential impact of city of New Orleans hurricane Katrina household and commercial wastes and demolition wastes that were deposited on top of the city's unlined, closed MSW Gentilly Landfill (Lee, 2006g,h,i). In both cases, the state regulatory agencies allow landfilling of C&D wastes in landfills that only have a compacted soil liner. In the case of the Gentilly Landfill, the Louisiana Department of Environmental Quality (LDEQ) issued a permit which enabled the city to increase the height of the Gentilly Landfill from 18 feet to 130 feet above ground level. LDEQ also significantly relaxed the restrictions on the types of so-called C&D landfill wastes that could be deposited at this landfill to include painted furniture, mattresses and many other types of household items that were destroyed by the flooding of homes associated with the hurricane Katrina situation.

A review of the potential ability of compacted soil (clay) liners to prevent leachate from passing through them into the underlying strata shows that leachate will penetrate a two-foot-thick clay layer with a design permeability of 10^{-6} cm/sec, within a few months (Workman and Keeble 1989). Further, Daniel (1990) has shown that such a liner can leak at the rate of about 1,000 gallons per acre per day. It is clear that compacted soil/clay liners are not effective in preventing groundwater pollution by C&D and other waste-derived leachate. This situation is similar to that reported above in the state of California SWAT studies on clay-lined landfills (Mulder and Haven 1995), where it was found that within a few years such landfills were causing groundwater pollution.

The state of California does not have specific C&D landfilling regulations. It does have regulations governing the disposal of "inert" wastes. Inert waste is defined as *"that subset of solid waste that does not contain hazardous waste or soluble pollutants at concentrations in excess of applicable water quality objectives, and does not contain significant quantities of decomposable waste"* (SWRCB Division 2, Title 27, §20230). Inert wastes do not require deposition in a managed area. It is, however, up to the proponent for managing such waste to demonstrate that the wastes comply with the inert waste definition. Since many construction and demolition wastes have leachable components, much of this type of waste is placed in MSW landfills in the State. In some areas of the State, MSW landfills require a double composite liner.

The only water quality threat posed by these inert wastes is siltation. According to Marshack (1989) of the Central Valley Regional Water Quality Control Board,

> *"Examples of 'inert waste' include construction and demolition wastes such as clean earth, rock, concrete and inert plastics, vehicle tires, uncontaminated clay products, and glass. 'Inert wastes' may be discharged to unclassified waste management units as long as they are prevented from entering surface waters. [Unclassified waste management units may have Waste Discharge Requirements from the appropriate Regional Board.] Again the emphasis is on beneficial use protection, rather than isolation of the waste from the surrounding environment."*

Marshack (1989) has discussed the approach used to determine whether a waste is an "inert waste." The California Department of Health Services and the State Water Resources Control Board have established regulations which provide detailed criteria on how wastes are to be classified, with the exception of the "designated waste" category. According to Marshack (1989),

> *"The lower boundary of this category is described only as the limit above which a waste could impair water quality at the site of discharge. This boundary can be more clearly defined by establishing 'Designated Levels' for specific constituents of a waste which provide a site specific indication of the water quality impairment potential of the waste.* [The Marshack (1989)] *report provides a methodology for calculating such levels. Designated Levels are calculated by first determining the bodies of water that may be affected by a waste and the present and probable future beneficial uses of these waters. Next, site-specific 'water quality goals' are selected, based on background water quality or accepted criteria and standards, to protect those beneficial uses. Finally, these water quality goals are multiplied by factors which account for environmental attenuation and leachability. The result is a set of Soluble and Total Designated Levels which are applicable to a particular waste and disposal site and which, if not exceeded, should protect the beneficial uses of waters of the State. Wastes having constituent concentrations in excess of these Designated Levels are assumed to pose a threat to water quality and are, therefore, classified as 'designated wastes' and directed to waste management units which isolate these wastes from the environment."*

According to this approach, inert wastes would be those that do not contain soluble components at concentrations that, when deposited at a particular location, would leach constituents that, through the Designated Level Methodology, would be considered a threat to ground and surface water quality in the disposal area. Implementation of this approach requires a site specific evaluation of the leaching characteristics of the types of wastes that are proposed to be classified as inert wastes, the hydrogeology of the proposed inert waste deposition area, as well as information on the present and probable future designated beneficial uses of the ground and surface waters that would be impacted by materials potentially released from the inert wastes. Wastes that do not meet the inert waste classification must be deposited in a managed waste disposal landfill, such as an MSW landfill or hazardous waste landfill.

An issue of increasing concern about waste wood is the potential for treated wood to leach arsenic, copper and chromium. Townsend and his associates at the University of Florida have conducted a number of studies on the leaching of these chemicals from treated wood (Townsend, et al. 1998; Khan, et al. 2004). They have found that the chemicals are somewhat leachable over a long period of time and represent a threat to groundwater quality. Lee (2007) has discussed the importance of properly managing waste treated wood in appropriately designed and monitored landfills, in order to prevent groundwater pollution by chromium and arsenic.

An issue of particular concern at C&D waste landfills is the management of hydrogen sulfide emissions from the landfill. Wallboard (which is composed of calcium sulfate), in the presence of decomposable organic matter and water, can produce large amounts of hydrogen sulfide, where the sulfate in wallboard is reduced by bacteria to sulfide. The US EPA (2005) is developing a guidebook on managing hydrogen sulfide at C&D waste disposal facilities. This guidance discusses the potential for hydrogen sulfide generated from the decomposition of wallboard in C&D landfills to not only cause an airborne nuisance to nearby individuals, but, at high concentrations, also a health threat. This guidance discusses approaches that can be used to minimize hydrogen sulfide production at C&D landfills.

Buske, et al. (2005) have presented a discussion of the characteristics of landfill odors and some of the approaches for assessing the magnitude of odor, and its control. The focus of their discussion is the potential adverse impacts of using fines from C&D wastes as landfill daily cover. They report that this approach has led to severe, persistent offsite odors, where it was necessary to terminate this approach.

It is evident that C&D wastes should not be considered inert. These wastes can leach components that can cause groundwater pollution. They should be managed in properly sited, designed, operated and closed landfills that receive postclosure care (maintenance and monitoring) for as long as the wastes in the landfill are a threat, upon contact with water, to generate leachate.

A subsequent section of this report (***Improving Public Health and Environmental Protection from Inadequately Developed Landfills***) discusses improving public health, groundwater resource and environmental quality protection associated with inappropriately sited and inadequately designed, operated and closed landfills and those landfills for which there is inadequate postclosure monitoring and maintenance for as long as the wastes in the landfill will be a threat. This section has particular applicability to C&D landfills, where regulatory agencies in a state do not adequately regulate such landfills to protect public health and the environment. An important difference between minimum design Subtitle D landfills and the C&D landfills that are allowed in a number of states is that the Subtitle D landfills with their single composite liner can postpone pollution of groundwaters for many years, while C&D landfills with only a compacted soil/clay liner will start to pollute the underlying groundwater aquifer system within a short time after waste deposition occurs in the landfill.

Hazards of Living/Working near Landfills

There are questions about the potential hazards of using a closed landfill as a playfield for children, constructing a school or playground adjacent to a closed (inactive) landfill, or purchasing residential property near an active and/or closed landfill. The public is justifiably concerned about the hazards of living next to, locating a school next to, or locating a playfield on a former landfill. Landfills, even those that contain so-called "nonhazardous" wastes, contain a variety of hazardous chemicals that, if not properly managed, can pollute groundwaters, soil and the atmosphere and therefore be a threat to those using properties near the landfill.

An issue of concern is whether those who live near landfills show evidence of adverse health effects. Lee and Jones-Lee (2007b) have recently discussed this issue. It is known from a number of studies conducted by the Centers for Disease Control (Anderson, pers. comm., 1999) that some populations living near landfills have shown a greater incidence of some diseases. Elliott et al. (2001) have reported that children of people living near landfills in England tend to have a higher rate of birth defects than the general population. Recently, *Environmental Health Perspectives* has published a paper (Kouznetsova, et al., 2007) which relates residential proximity to hazardous waste sites to hospitalization associated with diabetes. A review of the various studies that have been conducted, however, reveals that the epidemiological approach for discerning health effects associated with populations living near landfills is not sufficiently sensitive to reliably determine whether releases from the landfill are at least in part responsible for the health effects. A complicating factor is that those living near landfills frequently are economically disadvantaged and of a different ethnic mix than the general population. Further, data that have been developed on this issue have often been devoted to former (closed) landfill situations, where there is far greater limiting of landfill emissions than will occur, at least initially, with today's Subtitle C and D landfills.

In the Lee and Jones-Lee (2007b) discussion of the hazards of living/working near landfills and hazardous chemical sites, they state,

> *"It is well-established that airborne releases from hazardous chemical sites (including active and inactive landfills) can have a significant adverse impact on the population within the sphere of influence of the site."*

The Agency for Toxic Substances and Disease Registry (ATSDR, 2006) has developed a discussion on gaseous emissions from landfills, in which they state,

> *"Many of the typical landfill gases, notably the alkyl benzenes and the sulfur compounds (both organosulfides and acid gases), may present an odor problem that can cause adverse health effects such as mucous membrane irritation, respiratory irritation, nausea, and stress. If an individual has a pre-existing health condition (e.g., allergies, respiratory illness), these additional health impacts can be significant."*

Lee and Jones-Lee (2007b) further state,

> *"With respect to the populations at risk from airborne releases of hazardous chemicals from a hazardous chemical site/landfill, as a first estimate, it would be all individuals who experience odors from the site. While many of the chemicals that are responsible for illness are non-odorous, typically, airborne releases from hazardous chemical sites/landfills have odorous components which are readily detectable. It is for this reason that hazardous chemical site and municipal, industrial and hazardous waste landfills should be practicing sufficient odor control so that there is no detectable odor at the site boundary – i.e., no trespass of odorous emissions onto adjacent properties. The odor control should not be done through masking agents, but with treatment technologies that destroy the odor and, it is to be hoped, the hazardous chemicals associated with the odor as well.*
>
> *It should not be assumed that the typical testing for airborne releases of hazardous chemicals associated with the evaluation of the impact of a landfill or other hazardous chemical site on adjacent properties is adequate to detect airborne hazardous chemicals released from the site. For some hazardous chemicals the analytical method detection limits are not adequate to detect the hazardous chemicals at concentrations of concern, either individually or in combination with other chemicals. The evaluation of whether odorous chemicals are being released from a site should be based on a properly documented assessment by individuals with above-average olfactory sensitivity."*

Recommended Approach. The recommended approach for utilizing landfill covers and areas adjacent to landfills for situations where children can be exposed to waste-derived constituents should involve a detailed, third-party, independent review of the magnitude of the releases that are occurring from the landfill to the atmosphere, to surface water runoff and to groundwater. This should require at least a one-year detailed monitoring effort that is conducted from the perspective of trying to find problems. This perspective is important since, in many cases, studies sponsored by landfill owners, as well as the studies conducted by consultants who typically work for potential site developers, are biased toward not finding problems – i.e., doing the minimum necessary to get by current regulatory agency requirements.

There is need for the site investigations to be conducted by a third-party managed team, where the management team has a proper balance of individuals who are knowledgeable and interested in full protection of public health and the environment. This does not mean that the team should be dominated by what are sometimes called "environmental activists." Some individuals who operate in this arena tend to distort the technical information available, and thereby have limited credibility in striking a proper balance.

Landfill Siting Issues

The US EPA, as part of the development of Subtitle D landfill regulations, failed to address one of the most important issues that should be addressed in developing a minimum Subtitle D landfill – namely, the siting of the landfill at geologically suitable sites for a landfill of this type. While the Agency does require that minimum Subtitle D landfills not be sited too close to airports, where there could be major bird problems for aircraft, or too near an earthquake fault or within a flood plain, the Agency did not address the issue of siting minimum Subtitle D landfills where the underlying geological strata do not provide natural protection of the groundwaters from pollution by landfill leachate when the landfill liner systems eventually fail. In accordance with current regulations, minimum Subtitle D landfills can be sited over highly important aquifers that serve as a domestic water supply source for an area. They can also be sited in fractured rock and cavernous limestone areas, where it is impossible, through the use of vertical monitoring wells, to reliably monitor the pollution of groundwaters by landfill leachate.

As discussed Anderson (1995) seismic activity in the vicinity of a landfill has been found to damage landfill containment systems. These impacts can occur in landfills located outside the areas where the US EPA Subtitle D landfills prohibit landfill siting.

The US EPA in developing Subtitle D landfill regulations, also failed to address one of the most important reasons why landfills lead to a justified NIMBY ("Not In My Back Yard") attitude. US EPA Subtitle D regulations allow the deposition of wastes very near the landfill property owner's property line.

Justified NIMBY

Hirshfeld et al. (1992), of Duke University, in a paper, "Assessing the True Cost of Landfills," have summarized the potential impacts of landfills that should be addressed as part of landfill development. They point out that the environmental and social costs of landfills are usually ignored, which in turn inhibits the development of other waste management options, such as waste reduction, recycling and resource recovery. They divide the impacts of landfills into "physical" impacts and "social" impacts. The physical impacts are related to ground and surface water pollution by leachate migration, atmospheric releases of landfill gas, and fires. Landfill gas is known to cause explosions resulting in loss of life and property, and damage to vegetation. Hirshfeld et al. also point out that the non-methane organic compounds in landfill gas contain toxic chemicals that are a threat to cause cancer. Further, other components in landfill gas, such as hydrogen sulfide and organosulfur compounds can cause unpleasant odors associated with landfills.

The social impacts of landfills include increased traffic, visible air pollution, noise, aesthetic degradation and limited land utility. The social-impacts cost of landfills, according to Hirshfeld et al., is *"(1) the cumulative decrease of surrounding property values; (2) the cost associated with land utility effects, also known as an 'opportunity cost'; and (3) a 'hastening cost'."* Several of these issues are discussed further below.

The state of Washington Department of Ecology in its Beyond Waste Project is conducting a comprehensive review of solid waste management practices in the state. As part of this effort a series of documents has been developed which discuss solid waste management issues. One of these publications, "Disposal – Yesterday, Today and Tomorrow" (Smith, 2004) states,

> *"The extent to which today's landfills adequately protect human health and the environment is a subject of debate, however. Requirements that govern siting, operation, closure, and post-closure are stringent and extensive. While the newest landfills are state-of-the-art facilities, they are far from benign in their impacts. Landfills may still affect the air, land, and water but to a significantly lesser degree than before today's standards went into effect."*

Typically, landfill proponents will characterize local opposition to a landfill as an ill-founded "Not In My Back Yard" (NIMBY) response of the public in the region. The authors have yet to find an individual located near a proposed landfill who does not become a "NIMBY." However, it is the authors' experience that, with few exceptions, all of those within a few miles of a proposed landfill are justified in their NIMBY response.

The authors have been involved in investigating over 80 landfills located in various parts of the US and in several other countries. They have also served as consultants to public groups and agencies on the potential impacts of proposed and existing landfills. Several years ago they published two papers, "Addressing Justifiable NIMBY: A Prescription for Siting MSW Landfills," (Lee and Jones-Lee, 1994d) and "Landfill NIMBY and Systems Engineering: A Paradigm for Urban Planning" (Lee et al., 1994), which discuss when NIMBY is justified. They also made a slide presentation at an urban planning conference, which summarizes key issues on justified NIMBY. These slides are available at
http://www.members.aol.com/duklee2307/NIMBY-UrbanPlanning.pdf.

The above-cited papers and presentation slides provide a discussion of the potential impacts of landfills and, most importantly, how many of these impacts can be controlled through proper landfill siting, design, operation, closure and postclosure monitoring and maintenance. As discussed by Lee and Jones-Lee (1994d), one of the key areas that can significantly reduce justified NIMBY is the provision for adequate buffer land between where wastes are deposited and adjacent properties. This buffer land is needed to dissipate the releases of waste-derived components in leachate ("garbage juice") and landfill gas.

Lee and Jones-Lee (2007c) have presented a discussion of the issues that need to be considered in evaluating the potential impacts of a landfill on those within the sphere of influence of the landfill. This review provides guidance on how those concerned about the siting of a landfill in their area should proceed to evaluate its potential impacts on their health, groundwater resources and interests.

Table 2, from the Lee et al. (1994) paper, lists the potential adverse impacts of landfills. As discussed above, the current typical municipal solid waste stream contains a wide variety of known and yet-to-be-identified hazardous and otherwise deleterious chemicals that are a threat to public health and the quality of groundwater that is used for domestic and agricultural purposes.

Table 2
Adverse Impacts of "Dry Tomb" Landfills on Adjacent/Nearby Property Owners/Users

- public health, economic and aesthetic aspects of groundwater and surface water quality
- methane and VOC migration - public health hazards, explosions and toxicity to plants
- illegal roadside dumping and litter near landfill
- truck traffic
- noise
- dust and wind-blown litter
- odors
- vectors, insects, rodents, birds
- condemnation of adjacent property for future land uses
- decrease in property values
- impaired view

From Lee et al. (1994)

Inadequate Buffer Lands. Landfill developers state that appropriate buffer zones have been planned for a proposed landfill, where a few hundred feet are allowed between where the wastes will be deposited and adjacent properties. While landfill developers claim that appropriate buffer zones have been planned, in fact even the most elementary understanding of the distances over which modern landfills can be adverse to adjacent property owners/users' health, welfare and interests shows that often several miles of buffer land is needed to dissipate the releases from a landfill on the landfill owner's property so that they are not adverse to adjacent property users/owners.

Other Impacts of Landfill Releases and Activities. Landfills can have a variety of additional impacts, such as fugitive trash, vermin, birds, noise, lights, etc., which are deleterious to the interests of those in the sphere of influence of the landfill. One of the major deficiencies of Subtitle D landfilling regulations is that the US EPA failed to address the justified NIMBY issues by failing to require that landfill owners provide adequate buffer lands between where the wastes will be deposited and adjacent properties. The typical approach that landfill owners/operators claim they will use as part of gaining a permit for siting a landfill, of limiting the size of the working face where each day's garbage is deposited, and then at the end of the day covering the daily deposited garbage with a thin layer of soil or other material, can, if fully implemented, reduce the magnitude of many of the adverse impacts associated with releases from the landfill during its active life, but does not eliminate them so that they are not adverse to adjacent property owners/users in those situations where there are inadequate buffer lands between the waste deposition area and adjacent properties. With at least a mile of land between where wastes are deposited and adjacent properties, it is possible to reduce the magnitude of justified NIMBY. To completely eliminate justified NIMBY would require, at many landfill locations, several miles of buffer lands owned by the landfill owner between where wastes can be deposited and adjacent properties.

Vermin-Disease Vectors. Vermin include animals such as rats and other rodents, and insects such as flies. In addition to being a nuisance, vermin can be vectors (carriers) of disease organisms and hazardous chemicals. Birds (gulls, crows, etc.) can be a significant problem at landfills, where large numbers will congregate and circle the landfill area, defecating on nearby residents and their properties, as well as schools, etc.

Noise Pollution. Hirshfeld et al. (1992) discuss landfill noise as part of their discussion of "Social Impacts" of landfills:

> *"Noise at landfills can be noticeable in nearby residential areas. The USEPA (1975) notes that excessive noise can have many undesirable effects on those exposed to it. In most cases, however, the noise is simply regarded as an annoyance."*

Noise pollution of the areas near a proposed landfill is a justified issue of concern because of the often limited buffer land between where wastes will be deposited and adjacent properties. This means that adjacent property owners can potentially experience noise pollution on their properties by the proposed landfill.

Light Pollution. Another issue of concern to the public is that some landfills operate at night, where nearby property owners would experience pollution by lights at the landfill. Some landfill operators plan to operate heavy equipment at night, under lights, for compaction of the wastes that had been received that day. This can lead to significant disruption of the interests of the nearby property owners/users, which should be controlled/prohibited.

Stormwater Flooding Problems. Frequently, landfill applicants will state that a landfill facility will be designed, constructed and maintained with a run-on control system to prevent flow onto the active portion of the landfill during the peak discharge from a 25-year storm, and a run-off control system from the active portion of the landfill to collect and control at least the water volume resulting from a 24-hour, 25-year storm. Some members of the public are concerned about a proposed landfill causing increased flooding of their property through diversion of stormwater. While, the landfill developer plans to collect all stormwater that occurs on the landfill property in detention basins, this collection only applies to storms that result in a magnitude of less than the 25-yr, 24-hr discharge. Storms of greater magnitude than this will result in runoff from the landfill property onto adjacent properties.

Some landfills are constructed with a berm around the landfill property to divert waters around the property that now run onto this property. This berm could lead to increased flooding problems downstream of the proposed landfill. This would be of justifiable concern to the public, unless the landfill owner is required to manage the waters that now run onto the landfill property, which would be diverted around it by a berm, in such a way as to restore the current flow regime and amount downstream of the proposed landfill. Without requiring this approach, some downstream property owners could be adversely affected by the proposed stormwater management approach.

Decreased Values of Nearby Property. One of the major concerns of property owners with the establishment of a landfill in their area is the decrease in their property values. Establishing a landfill with inadequate buffer lands between the waste deposition area and adjacent properties leads to decreased property values. This is a consequence of landfill owners/operators' failing to adequately control landfill releases to the air (odors, explosive gases, hazardous volatile chemicals, etc.) and groundwater (pollution), and landfill-associated activities such as truck traffic, noise, lights etc. While some landfill owners will claim that establishing a proposed landfill will not affect nearby property values, this is not in accord with the results of the studies conducted by Hirshfeld et al. (1992). They reported, based on studies at various locations, that decreased property values have been found as far as three miles from the landfill.

Individuals who own land immediately adjacent to a proposed landfill, as well as most others who own property within several miles of a landfill, can be expected to have their property values significantly decreased by the development of the landfill. This is of particular economic significance to some property owners, since their property could be developed with substantial residential and commercial activities if it were not for the presence of the landfill.

Host Fees. A tactic that is widely used by landfill developers is to offer the local community a "host fee" of a dollar or so per ton of waste deposited in a landfill, which the community can use for various purposes. In developing this arrangement, the landfill developer is careful not to site the landfill near the properties of those community officials who are responsible for voting to accept the host fee. The magnitude of the host fee made available is typically small compared to the ultimate cost that will have to be spent in mitigating the effects of the landfill and the Superfund-like groundwater cleanup costs that will occur for future generations. Further, it is rare, if ever, that the host fee is used to compensate those within the sphere of influence of the landfill for their lost property value and other adverse impacts on their health, groundwater resources and interests.

Impact on the Three Rs

Today's initially cheaper-than-real-cost solid waste management is strongly contrary to effective conservation and reuse of solid waste components. Lee and Jones-Lee (2000) have discussed the importance of reducing, reusing and recycling (the "Three Rs") as much of the components of solid waste as possible as a resource conservation measure and for protection of groundwater resources, public health and the environment, under the conditions where the true cost of landfilling of solid waste in dry tomb landfills is paid as part of disposal fees.

Environmental Justice Issues
A key issue that needs to be evaluated with respect to environmental justice is whether the siting of a landfill will result in impacts that violate Title VI requirements for protection of minorities against sources of environmental problems. Property owners should have the right to be able to use and develop their property without the adverse impacts of a landfill. Lee and Jones-Lee (2004e) have discussed an environmental justice situation with respect to locating a MSW landfill in Mobile, Arizona.

Professional Ethics Issues
It is appropriate to inquire why there is not greater discussion of the significantly flawed approach of Subtitle D landfilling. It is the authors' experience that these issues are well-understood by many of those in regulatory agencies and in the landfill consulting community; however, as discussed by Lee and Jones-Lee (1995b), there is a significant professional ethics issue associated with the permitting of landfills, where those who develop landfills for public and private agencies do not discuss these problems, since it would mean that their firm would not gain further work from landfill developers.

Landfill permitting in the US is conducted in an adversarial arena, where landfill applicants and their consultants discuss only the positive aspects of a proposed landfill, and do not discuss the problems associated with the landfill. This provides the regulatory agencies responsible for permitting landfills with an unreliable information base upon which to make decisions on the permitting of a landfill. Lee and Jones-Lee (1995b) recommend that the current adversarial landfill permitting approach be replaced by a publicly conducted interactive peer review process, where both the positive and negative aspects of a proposed landfill can be discussed. Adoption of this approach would greatly improve the reliability of the information provided to regulatory agencies as part of permitting of landfills.

An issue of concern in the permitting of landfills is whether consulting firms that work for landfill developers can serve as independent reviewers of a proposed landfill, advising regulatory agencies, county boards, etc., on the potential impacts of a particular landfill. Lee and Jones-Lee (2006c) have discussed this situation, pointing out that it is extremely difficult if not impossible for consulting firms or individuals that normally support the development of landfills to perform true, independent assessments of landfills, since such reviews could readily lead to their not being able to gain future contracts with landfill developers.

Improving Landfilling of MSW
There are a number of approaches that members of the public potentially impacted by a landfill can work toward achieving, which will improve the ability of landfills to provide containment of the wastes for as long as the wastes in the landfill will be a threat. These are briefly summarized below.

Siting. The landfill should be sited so that it provides, to the maximum extent possible, natural protection of groundwaters when the liner system fails. Siting landfills above geological strata that do not have readily monitorable flow paths for leachate-polluted groundwaters should be avoided. Of particular concern are fractured rock/clay and cavernous limestone areas, as well as areas with sandy lenses.

Design. The landfill should be a double composite lined landfill, with a leak detection system between the two liners.

Closure. A leak detectable cover should be installed on the landfill which will indicate when the low-permeability layer of the landfill cover fails to prevent moisture from entering the landfill.

Monitoring. The primary monitoring of liner leakage should be based on the double composite liner, where the lower composite liner is the leak detection system for the upper composite liner. If vertical monitoring wells are used, then the spacing between the vertical monitoring wells at the point of compliance should be such that a leak in the HDPE liner caused by a 2-ft-wide rip, tear or point of deterioration at any location in the landfill would be detected at the point of compliance with a 95-percent reliability.

Landfill Gas Collection. For those landfills that contain wastes that can produce landfill gas, a landfill gas collection system should be designed, installed and maintained for as long as the wastes in the landfill have the potential to generate landfill gas. The landfill gas collection system should be designed to have at least a 95-percent probability of collecting all landfill gas generated at the landfill. It is recommended that the gas collection system for a closed landfill be operated under vacuum, including in the leachate collection and removal system, to reduce the penetration of landfill gas through the liner system, which could lead to groundwater pollution.

Maintenance. The maintenance of the landfill cover, monitoring system, gas collection system, etc., should be conducted for as long as the wastes in the landfill will be a threat, with a high degree of certainty of detecting landfill containment system and monitoring system failure.

Funding. The funding for closure, postclosure monitoring, maintenance and groundwater remediation should be established at the time the landfill is developed, from disposal fees that are deposited in a dedicated trust fund of sufficient magnitude to address plausible worst-case scenario failures for as long as the wastes in the landfill will be a threat. Unless appropriately demonstrated otherwise, it should be assumed that the period of time for which postclosure care funding will be needed will be infinite.

Adoption of these approaches (or as many of them as possible) will significantly improve the ability of landfills to protect groundwater quality, public health and the environment for as long as the wastes in the landfill will be a threat.

Improving Public Health and Environmental Protection from Inadequately Developed Landfills. In those situations where a landfill will be developed that does not provide for full public health, groundwater resource and environmental protection, such as a minimum design Subtitle D landfill with a single composite liner, the following approach should be incorporated into the permitting of the landfill.

In order to significantly improve public health, groundwater and surface water quality protection, a landfill proponent should be required to:

- Conduct sufficient additional hydrogeological investigations to be able to reliably predict (under plausible worst case conditions - most protective) the pathways for adjacent property groundwater pollution, when offsite groundwaters will likely be polluted and when surface water springs and streams in the area of the landfills will be polluted by landfill leachate that penetrates the landfill liners.
- Establish a proactive, comprehensive offsite water quality monitoring program of all offsite water supply wells, springs and surface water streams within several miles of the proposed landfills, which will detect incipient groundwater and surface water pollution by landfill leachate. This distance should be determined based on the hydrogeological conditions that exist in the area of the proposed landfill.

MSW and other types of landfills will contain wastes that generate leachate that will be a significant threat to pollute groundwaters and surface waters in the vicinity of the landfill. This leachate will contain chemicals that can cause groundwater consumed by humans and animals to be a health threat. In addition, leachate-polluted groundwater will contain chemicals that will cause tastes and odors and make the leachate-polluted groundwater unusable for domestic and many other purposes, including as a water supply for animals. Such pollution will cause the well to have to be abandoned.

Landfills that are designed to meet the Subtitle D minimum requirement of a single composite liner will ultimately allow leachate generated within the landfill to penetrate into the groundwater system underlying the landfill. Typically associated with this type of landfill are the highly unreliable groundwater monitoring systems that are allowed by regulatory agencies, involving vertical monitoring wells spaced hundreds to thousands of feet apart at the point of compliance for groundwater monitoring. The hydrogeology of the groundwaters underlying many proposed landfills is complex, with sand layers and fractured rock/clay. The groundwater under such landfills will carry leachate-polluted groundwater that develops under the landfill to groundwaters that underlie adjacent properties and, at some landfill locations, to surface waters. At some time in the future, the groundwaters under adjacent properties will be polluted by chemicals in the landfill leachate. This will render the offsite groundwater a health threat and unusable for domestic and many purposes. Surface waters polluted by polluted groundwaters will be a threat to domestic water supplies and to aquatic life.

<u>Need for Improved Hydrogeological Characterization</u>. The complex hydrogeology underlying and in the area of many proposed landfills makes the transport of leachate-polluted groundwater to offsite areas difficult to assess/monitor. Typically the degree of characterization of the geological strata underlying a proposed landfill is inadequate to predict potential pathways and the rate of movement of leachate-polluted groundwater that will occur under the landfill to offsite areas. As part of providing an appropriate degree of offsite groundwater resource and public health protection, it is reasonable to require that a landfill proponent be required to characterize the hydrogeology of the landfill’s area sufficiently well so that reliable estimates of the direction, rate and degree of pollution of adjacent and nearby properties’ groundwaters can be made once the liner system has failed to collect all the leachate generated in the landfill. This information is essential to developing an appropriate groundwater monitoring system to detect when the leachate-polluted groundwater first reaches the point of compliance for groundwater monitoring down groundwater gradient from the landfill.

The landfill permitting agency(s), as part of consideration of permitting a landfill, should require that a comprehensive hydrogeological investigation be conducted at the landfill site so that there is a reasonable degree of scientific certainty in predicting the potential pathways by which leachate-polluted groundwaters that occur at any location under the landfill liner can trespass under adjacent properties.

The hydrogeological investigation should also provide a plausible worst-case estimate of the concentrations of selected leachate chemicals that could occur at adjacent property lines and how fast leachate-polluted groundwater would reach the adjacent property lines when the liner system fails to collect all leachate generated in the landfill.

Requiring this degree of hydrogeological characterization is in accord with most landfill permitting agencies' mission of public health and groundwater resource protection.

A proposed landfill should not be permitted until the additional hydrogeological information is made available and independently reviewed for its technical adequacy and reliability. This information on the

- pathways for leachate-polluted groundwaters to move from under the landfill to offsite properties,
- when pollution of offsite groundwaters is expected to occur, and
- the potential concentrations that will occur under adjacent properties of various types of pollutants that are present in the expected leachate

is needed to determine whether a proposed landfill should be permitted. If it is permitted, then with this information the potentially impacted public, regulatory agencies and others would have a better understanding of the threat that the landfill represents to the groundwater resources under their property and the surface water resources of the area.

<u>Offsite Groundwater, Water Supply Well, and Surface Water Monitoring.</u> In addition to greatly improving the information on the hydrogeology of a proposed landfill site and the surrounding area, there is need to require that the landfill owner establish comprehensive offsite groundwater monitoring of all water supply wells within the sphere of influence of the proposed landfill. This sphere should be considered to be several miles in any direction from the landfills, dependent upon the hydrogeological conditions that exist in the area. The purpose of this monitoring program would be to detect incipient pollution of existing water supply wells located on nearby properties. This approach is justified as part of providing improved public health and groundwater resource protection and assurance to the potentially impacted public that the landfill has not yet polluted their groundwater. It would provide a means of verifying the reliability of the predicted pollution of offsite groundwater.

In addition to the landfill compliance monitoring wells at the point of compliance for groundwater monitoring, additional groundwater monitoring wells should be developed along the most probable pathways for leachate-polluted groundwaters to move toward offsite properties. If leachate-polluted groundwater is detected in any compliance monitoring wells and/or the pathway monitoring wells, then the landfill owner should be required to begin groundwater remediation, likely through pump and treat of the leachate-polluted groundwaters. This remediation would be designed to stop further offsite movement of leachate-polluted groundwaters. This is important because, as discussed by Rowe (1991), MSW leachate-polluted aquifers can never be remediated to a sufficient extent to enable the use of groundwater that has come in contact with the polluted but "remediated" part of the aquifer to be a reliable, safe source of domestic and animal water supply.

This monitoring program should be conducted quarterly for a broad range of parameters until a sufficient database has been developed so that the concentrations of the monitored parameters can be reliably predicted for the next quarterly monitoring. After one year of reliably predicting the results of the quarterly monitoring, the frequency of monitoring of offsite potentially impacted wells can be reduced to semiannually.

In order to protect surface water quality from pollution by landfill leachate, comprehensive monitoring of all springs and streams within several miles of the landfill should be required for those hydrogeological situations where polluted groundwaters could discharge to surface waters. This monitoring would provide an early warning of pollution of surface waters by landfill leachate. The pollution of surface waters can affect both domestic water supply water quality as well as aquatic life-related beneficial uses of a waterbody. For many constituents, the water quality criterion for protection of aquatic life is one or more orders of magnitude lower than the drinking water MCL.

This monitoring program should be funded by the landfill owner but carried out by third-party consultants that report the results to a Monitoring Committee consisting of the regulatory agencies, property owners and the landfill owner. This monitoring program should be conducted forever – i.e., as long as the landfill has the potential to generate leachate that can pollute groundwaters underlying the landfill.

The offsite well monitoring would be for all existing and any new water supply wells that are developed in the future. This approach is justified since those who own properties adjacent to and near the landfill are entitled to continuing to have groundwaters under their property that are free of landfill leachate.

Monitoring of the characteristics of the leachate generated in a landfill should include a broad range of potential pollutants that can be expected to be generated based on the characteristics of the wastes accepted at the landfill. The monitoring of groundwaters and surface waters should include a broad range of potential pollutants and potential transformation products. An expert panel would advise the Monitoring Committee on the parameters that should be included in the monitoring. The required monitoring parameters should be reviewed each year by the panel to determine if there are any new potential pollutants that should be added to the list of parameters.

Hazardous Waste Landfilling

RCRA distinguishes between hazardous and nonhazardous wastes. As discussed above, the distinction between the two types of wastes is somewhat arbitrary and certainly does not prevent hazardous chemicals from being deposited in so-called nonhazardous waste (Subtitle D) landfills. The US EPA has developed regulations for landfilling of hazardous wastes in Subtitle C landfills. This type of landfill involves a double composite lined system for waste containment. Further, the US EPA requires some pretreatment of some of the hazardous waste components that are placed in Subtitle C landfills, to reduce their mobility. This pretreatment, however, does not prevent the development of leachate associated with water percolating through the landfilled wastes, which can enter the underlying groundwaters as the Subtitle C landfill liner system deteriorates.

Lee (2006j) has recently provided a comprehensive discussion of the potential problems associated with the Peoria Disposal Company's existing and proposed expansion of a Subtitle C hazardous waste landfill located near Peoria, Illinois. As discussed, Subtitle C landfills have essentially the same problems as Subtitle D landfills, of ultimate failure of the landfill liner and cover systems while the wastes in the landfill are still a threat to generate leachate upon contact with water. There is, however, a potential advantage of Subtitle C landfills, as well as Subtitle D landfills that are constructed with a double composite liner system, in that, when leachate is detected in the leak detection zone between the two composite liners, it is known that the upper composite liner has failed or is failing, and it is only a matter of time before the lower composite liner also fails, if it has not already done so.

As discussed above, when leachate is detected in the leak detection zone between the two composite liners in either a Subtitle C or a double composite lined Subtitle D landfill, there is need to stop leachate production through repairing the low-permeability plastic sheeting layer in the landfill cover. To address the chronic problem of periodic failure of the plastic sheeting layer in the cover which could lead to groundwater pollution, it is recommended that a leak detectable cover be installed on all double composite lined landfills prior to or at the time when leachate is detected in the leak detection system between the two composite liners.

This approach requires that adequate postclosure funding be available, throughout the period that the wastes in a Subtitle C or D landfill are a threat, to install and operate the leak detectable cover. Leak detectable covers can and should also be installed on all Subtitle D landfills when it becomes obvious that the landfill cover system is no longer preventing leachate generation caused by moisture penetrating through the cover into the wastes. This approach, however, requires that the leachate collection system continue to be operated and maintained throughout the essentially infinite period of time that the wastes in the landfill are a threat to generate leachate upon contact with water.

Addressing the Flawed Technology of Subtitle D Landfilling

The potential problems with dry tomb type landfilling were noted at the time that this approach was first proposed in the early 1980s. At that time the authors had just completed research on behalf of the US EPA National Groundwater Research Program located at Ada, Oklahoma, devoted to factors influencing the ability of compacted clay liners for landfills to prevent groundwater pollution. The authors were involved in the review of a proposed hazardous waste landfill located in eastern Colorado. They also were involved in reviewing several other hazardous waste and municipal waste landfills in other parts of the country. Based on their research and the proposed landfills that were being developed at that time with compacted clay liners, Lee and Jones (1984) developed a review paper, "Is Hazardous Waste Disposal in Clay

Vaults Safe?" that was published in the Journal of the American Water Works Association. Subsequently the Water Resources Division of the AWWA judged this paper as the best paper published in the Journal during 1984. The thrust of this paper was that the attempt to isolate solid wastes in dry tomb type landfills was doomed to ultimate failure.

As it stands now, the current regulatory approaches allowed by the US EPA and states can at best provide for protection of public health and the environment from hazardous and deleterious components of municipal and industrial wastes for a relatively short period of time compared to the time that the landfilled waste components will be a threat. Unfortunately, the early warnings on the flawed technology of dry tomb landfilling were ignored with the result that the US is building up a massive legacy of municipal landfills that will become "Superfund" sites. There is need to rewrite Subtitle D so that truly protective landfills can be developed that will protect public health, groundwater resources and the environment for as long as the wastes in the landfill will be a threat.

There is an urgent need for the U.S. (as well as other countries) to begin to manage non-recyclable municipal and industrial solid wastes, construction and demolition wastes and hazardous wastes in landfills that are sited, designed, operated, maintained and closed, with adequate postclosure care/funding for as long as the wastes are a threat, where the generators of the wastes are required to pay the full cost of appropriate waste management and thereby stop the current practice of passing a substantial part of the costs on to those who are within the sphere of influence of a landfill as well as future generations. There is obvious need for a major overhaul of Subtitle D MSW landfilling to abandon dry tomb landfilling in favor of increased practice of the three Rs and development of landfills that can be used to treat the non-recyclable MSW to produce non-polluting residues.

Fermentation Leaching of MSW. There is growing recognition that rather than trying to keep the wastes dry forever, the landfill should become a reactor system where the components in the solid wastes can be treated while the liner system still maintains its integrity. This has led to what are called "bioreactor" landfills where moisture (recycled leachate) is added to the landfill to enhance landfill gas production and to leach the leachable components of the wastes. However, as discussed by Jones-Lee and Lee (2000), many of the so-called bioreactor landfills that are being developed today that are occurring in minimum design Subtitle D landfills with a single composite liner tend to increase the potential for groundwater pollution by the leachate generated in the landfill. Jones-Lee and Lee (2000) and Lee and Jones-Lee (1993c) have discussed how landfills can be developed that will treat municipal solid wastes to produce a non-polluting residue and protect groundwaters from pollution during the treatment.

They describe a fermentation leaching approach where shredded wastes are placed in a double composite lined landfill with a leak detection system between the two composite liners. Shredding the wastes before they are placed in the landfill eliminates the impact of plastic-bagged garbage hiding wastes from added moisture, and provides for a more even flow of moisture through the wastes for promoting fermentation and leaching. As part of implementing this approach, there is need to develop a plumbing header system to distribute the recycled leachate over the wastes, providing for fairly even distribution of the recycled leachate through the shredded wastes.

When the production rate of landfill gas slows, leachate recycle should be terminated, and a clean-water rinsing of the residual, non-fermentable waste components should occur (where no recycle is practiced), and the collected rinse water is treated, presumably at a POTW. The addition of clean water to the landfill will leach soluble and mobile components from the wastes that could otherwise, at some time in the future, lead to groundwater pollution when the liner system is no longer effective in collecting leachate.

As with all MSW landfilling, a dedicated trust should be established that is of sufficient magnitude to address all plausible worst-case-scenario failures that can occur for as long as the wastes in the landfill are a threat. For this approach, this would likely be for five to ten years after the rinse water collected in the leachate collection system shows little or no potential to pollute groundwater. As discussed above, without following the fermentation leaching approach, the period that the wastes will be a threat is, effectively, forever. The fermentation leaching approach that Lee and Jones-Lee advocate provides an opportunity to effectively treat the wastes while the liner systems are likely to retain their integrity, and thereby shorten the period that the landfill is a threat to cause groundwater pollution.

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